New frontiers in dark matter direct detection:

Probing sub-GeV DM Masses

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8th Patras Workshop on Axions, WIMPs and WISPs
18 July, 2012
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Overview

- The WIMP love story
- The unexplored DM mass range
- XENON10, again

The WIMP love story...

PHYSICAL REVIEW LETTERS

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Cosmological Lower Bound on Heavy-Neutrino Masses

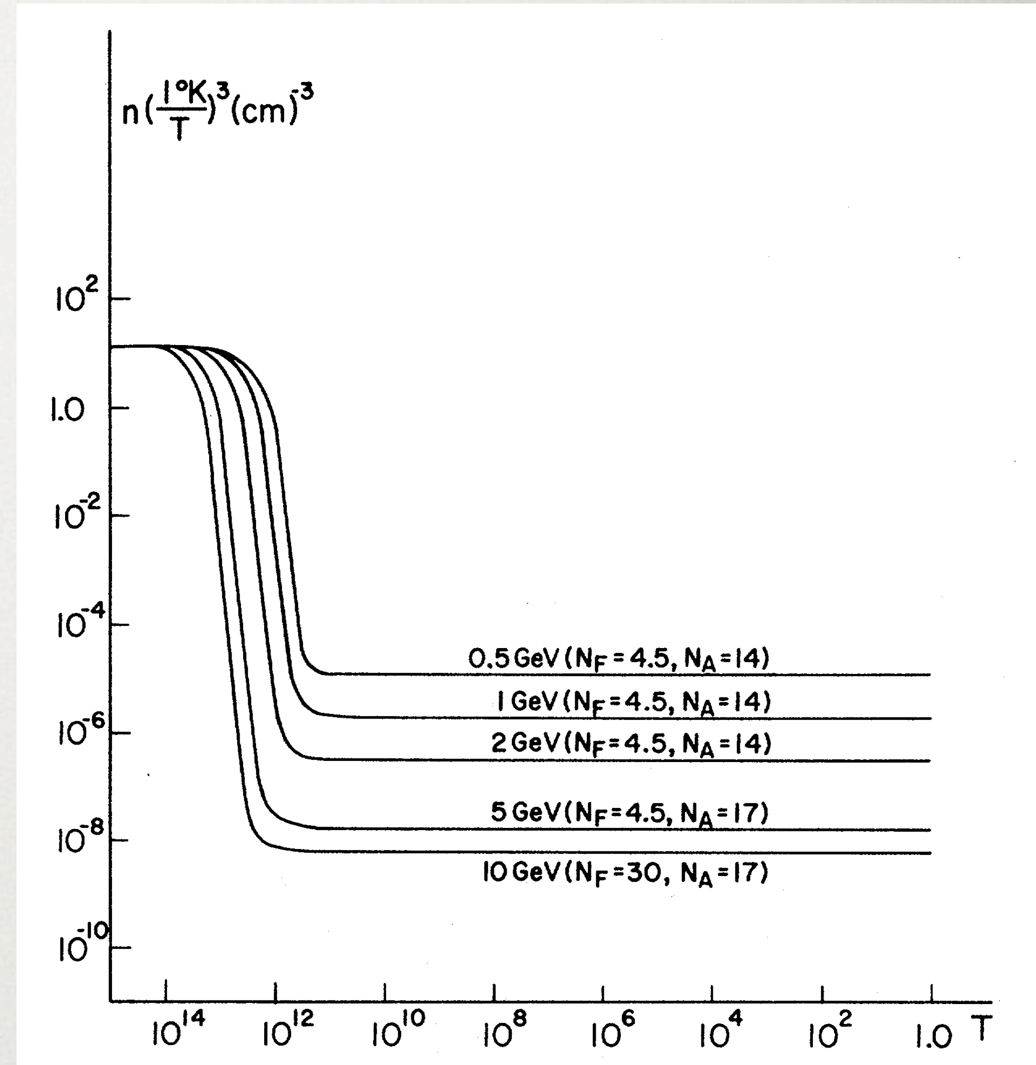
Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] Batavia, Illinois 60510

and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



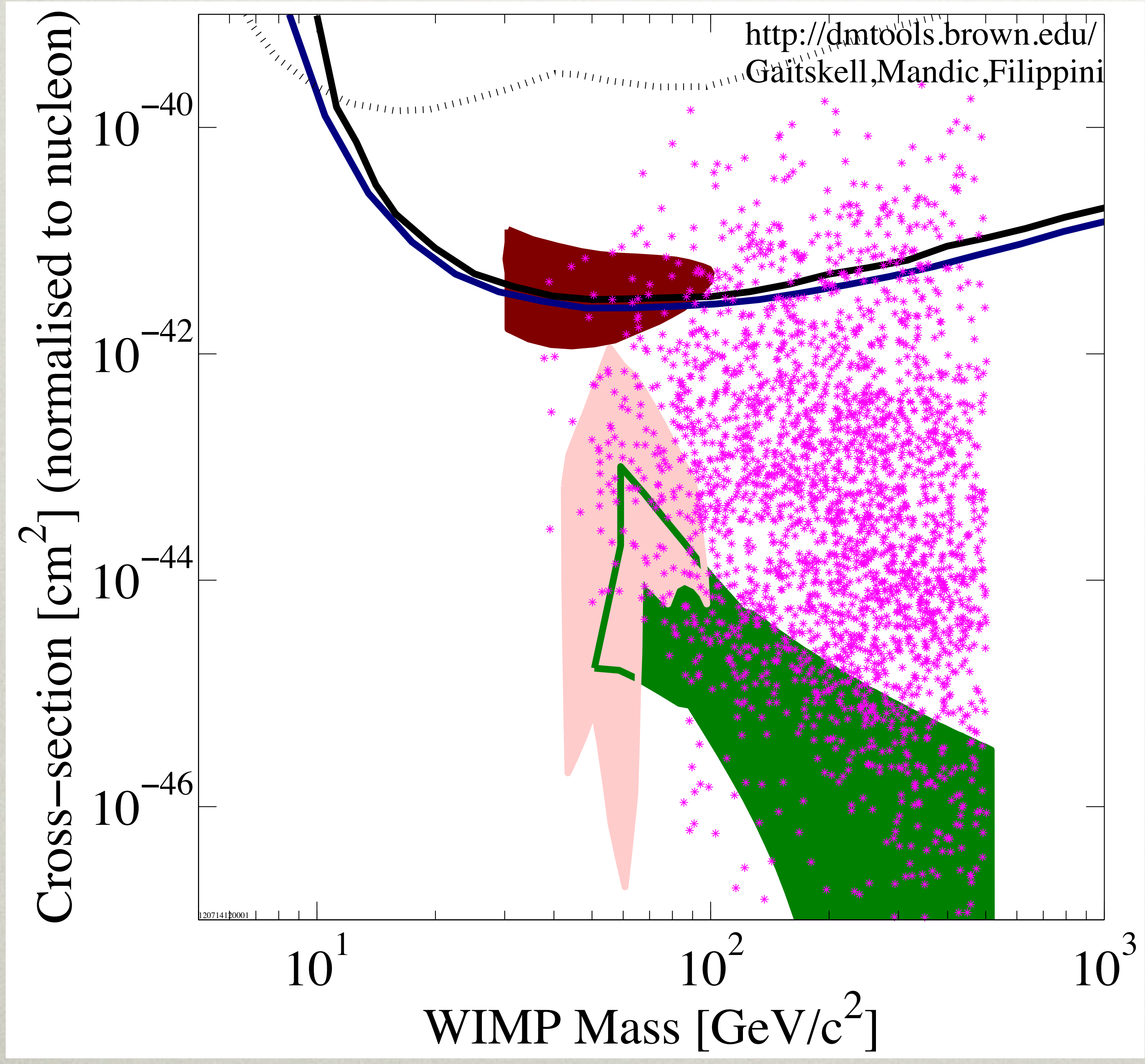
Physicists

Relationship Status	In a relationship with WIMPs
Anniversary	July 25, 1977

Model-independent thermal production is a powerful aphrodisiac, and has guided many experimental efforts

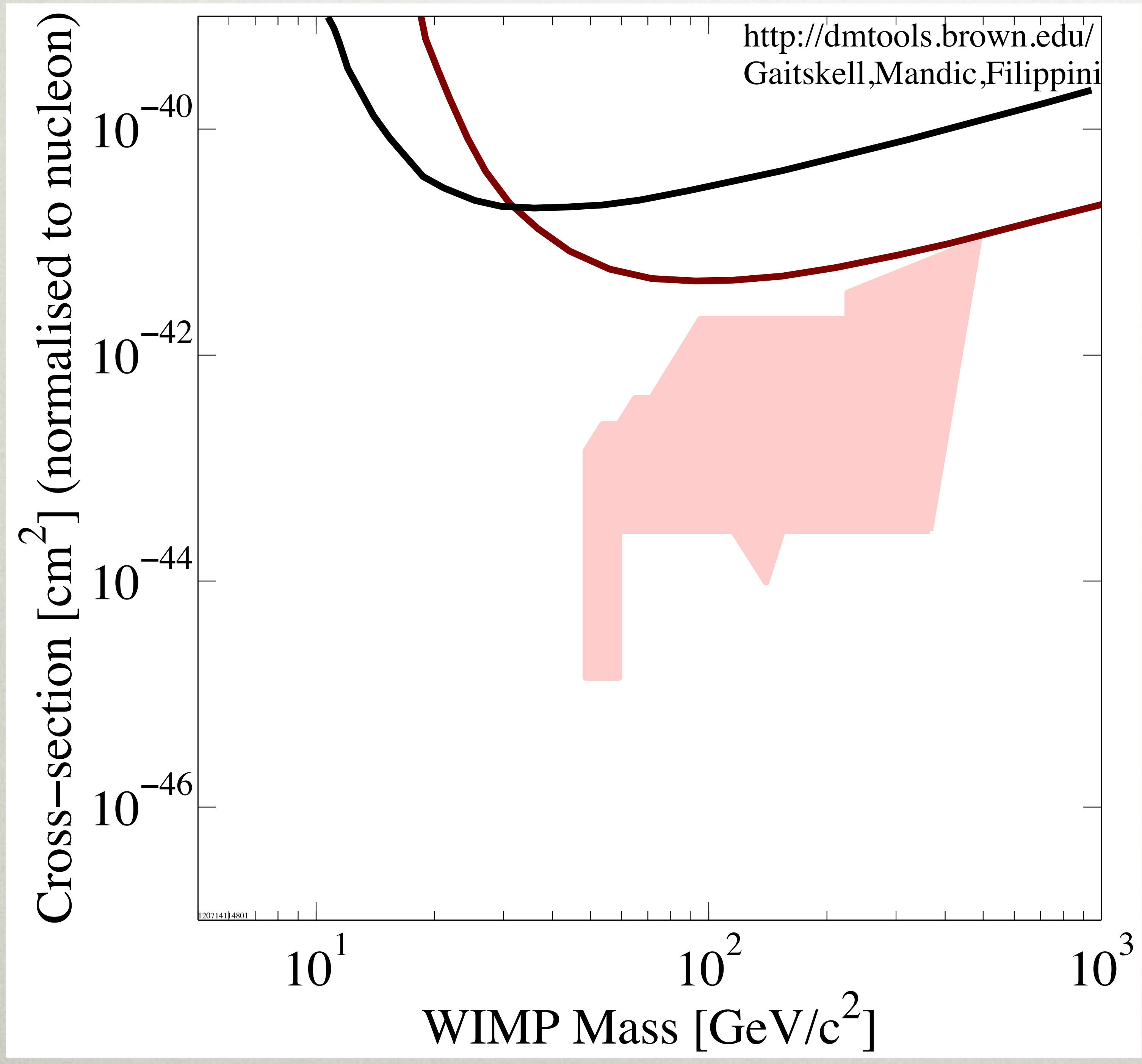
In the year 2000....

Time-progression of sensitivity



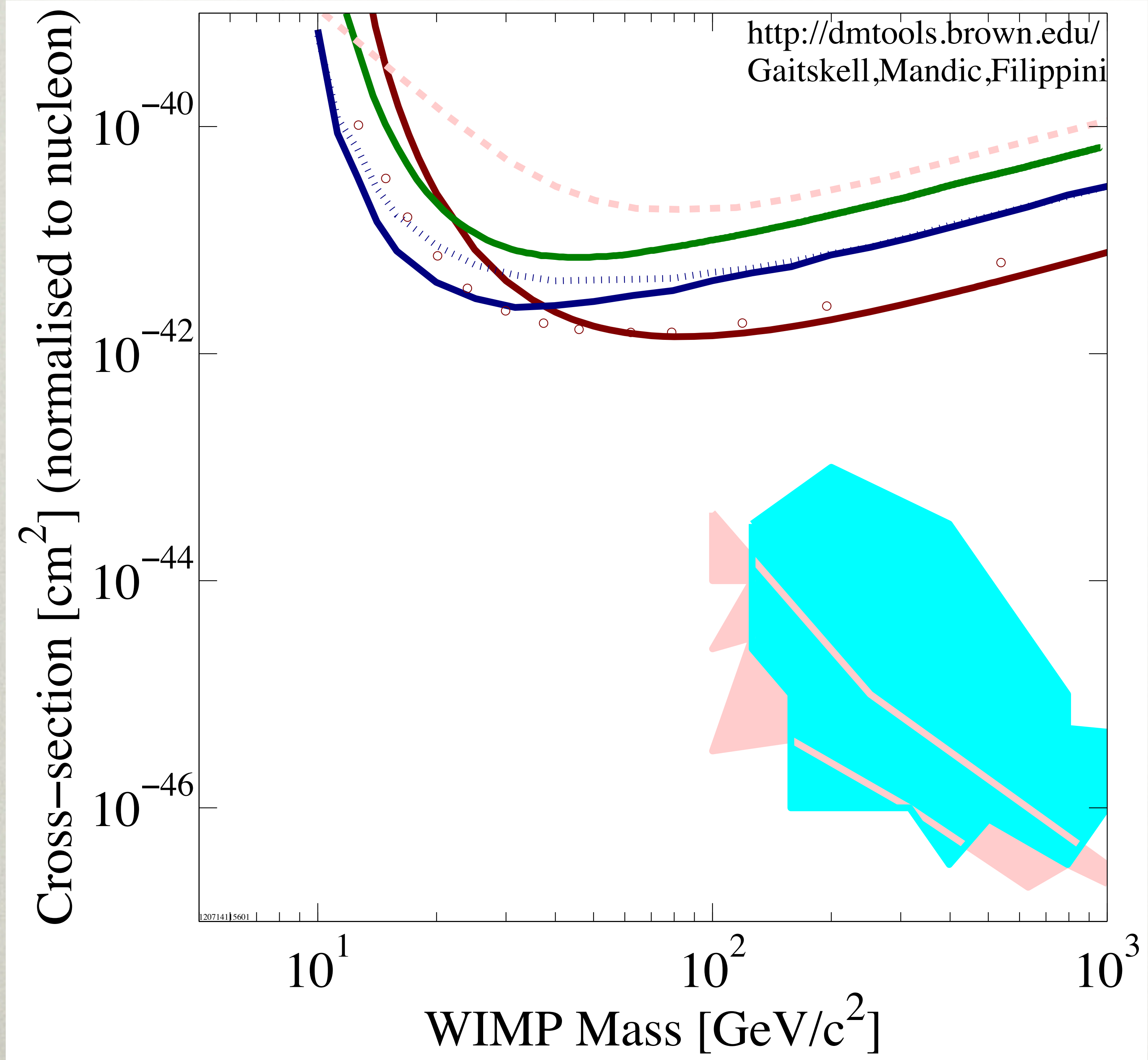
Year 2000

Time-progression of sensitivity



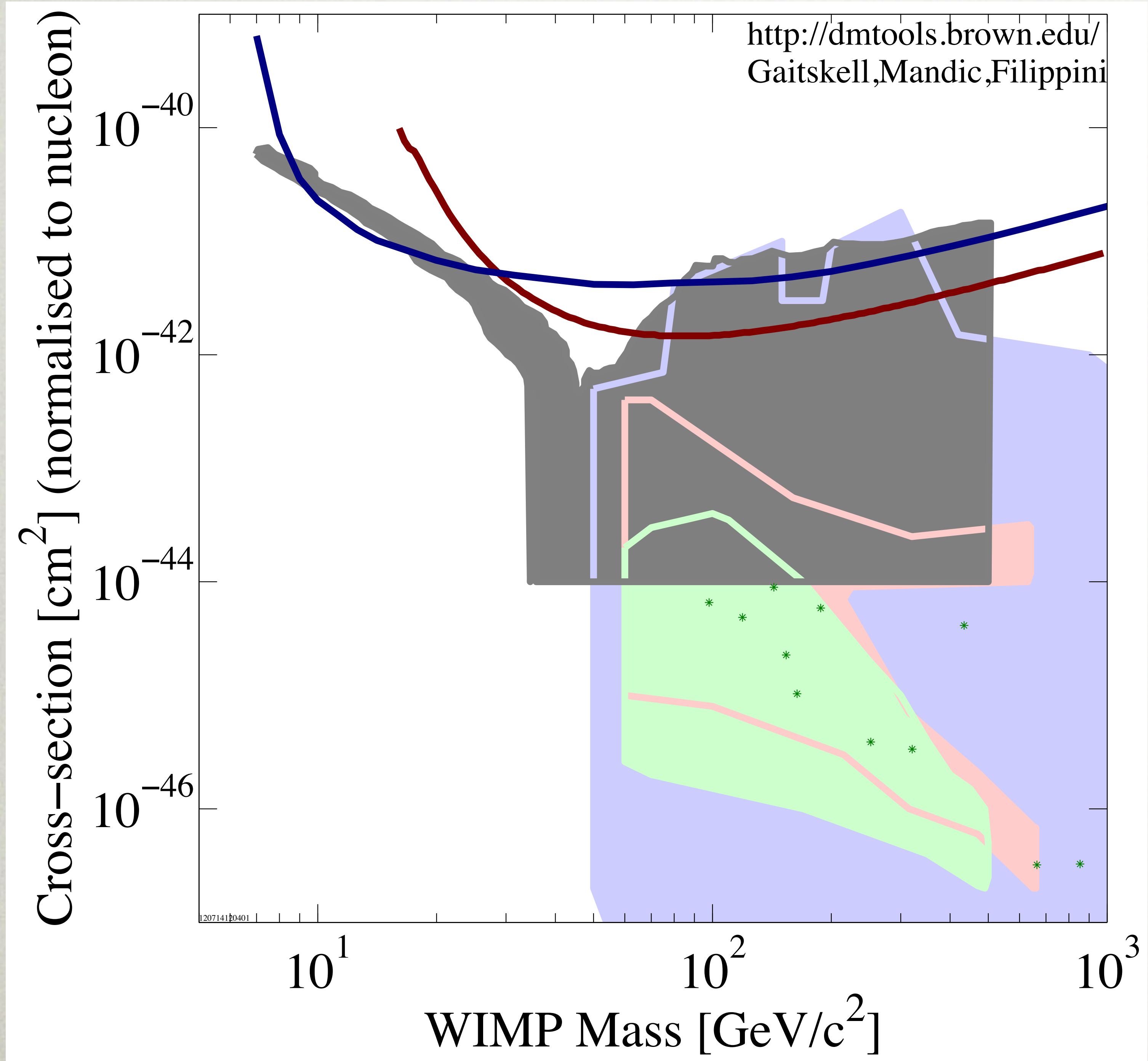
Year 2001

Time-progression of sensitivity



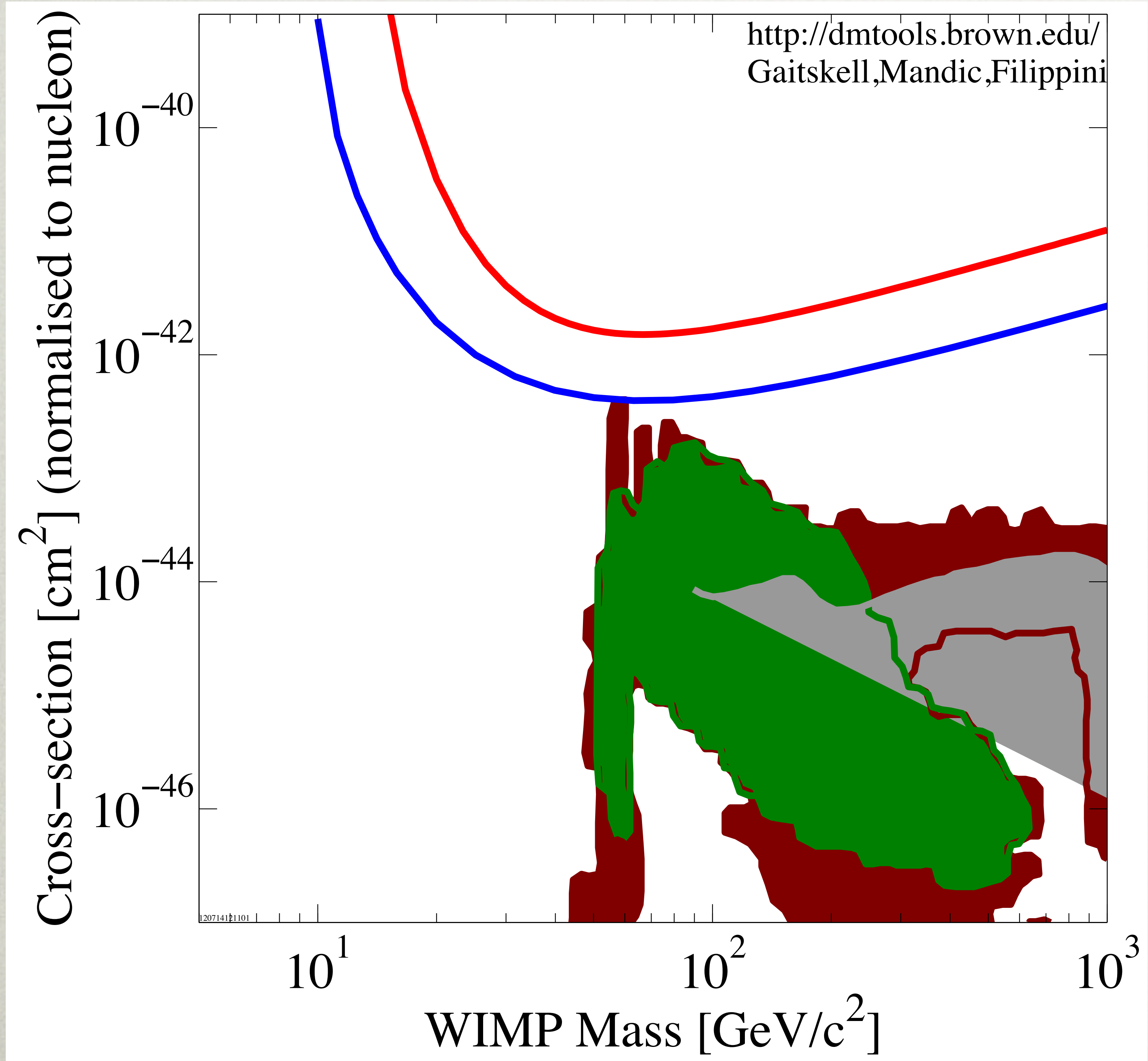
Year 2002

Time-progression of sensitivity



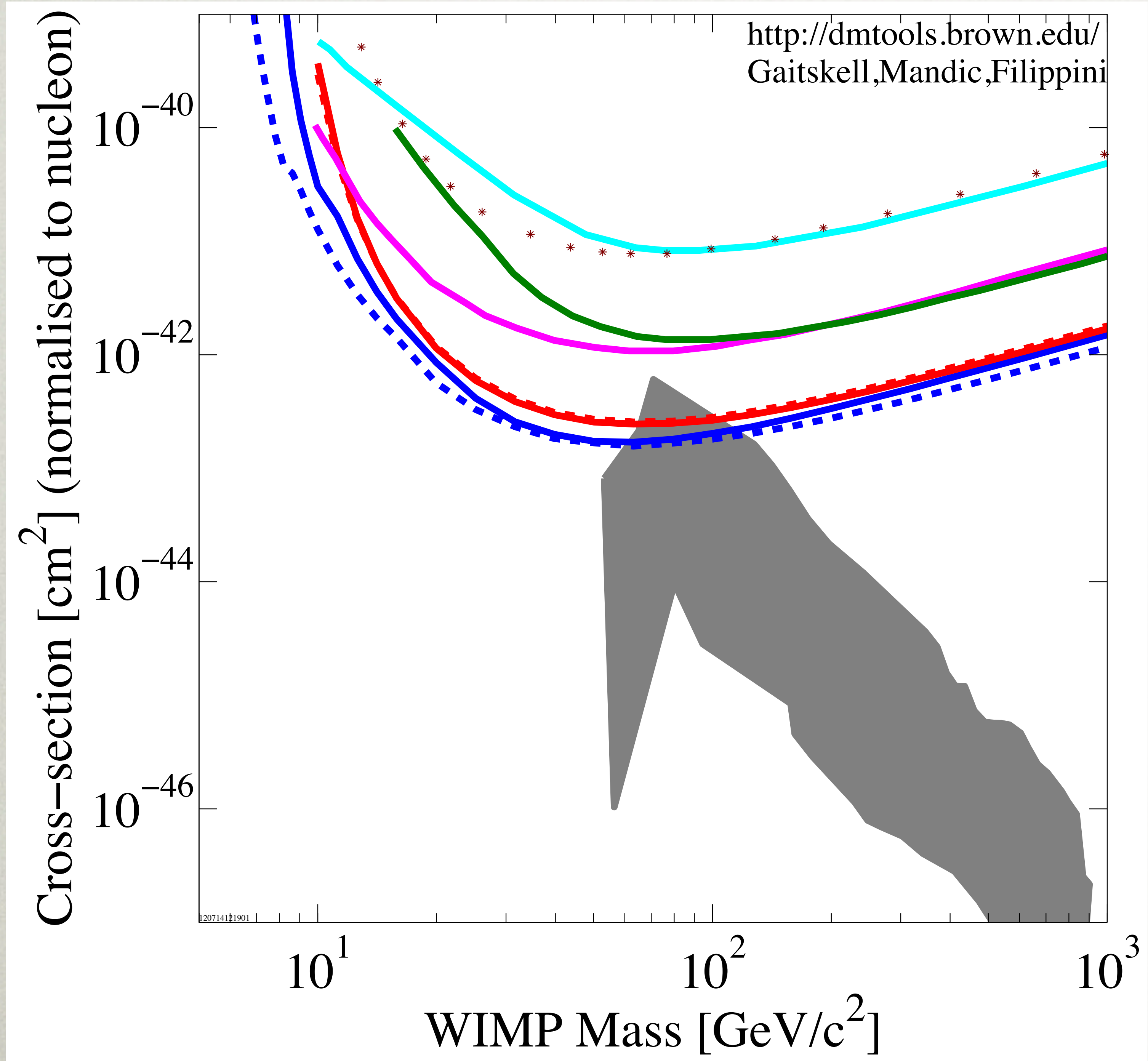
Year 2003

Time-progression of sensitivity



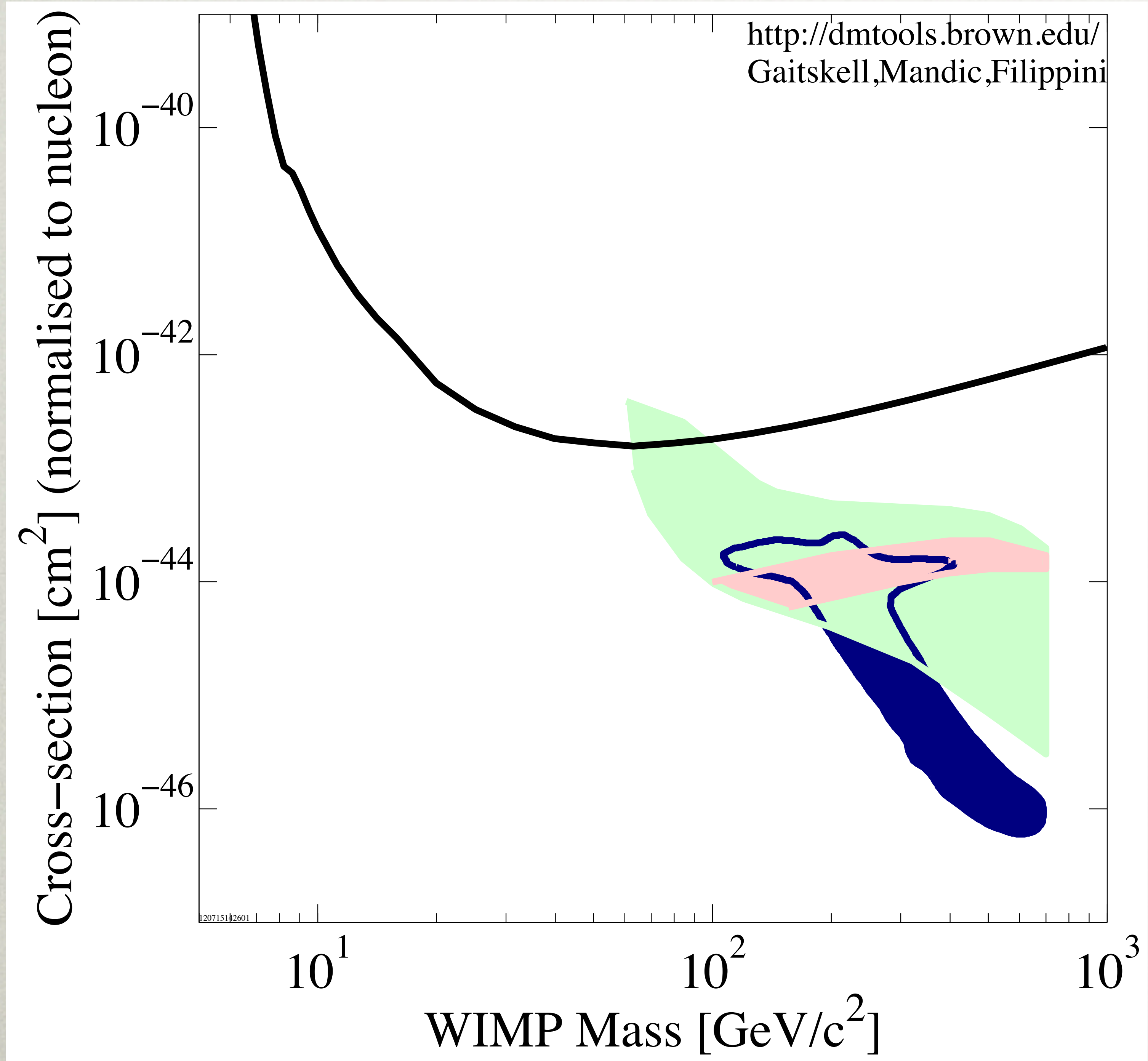
Year 2004

Time-progression of sensitivity



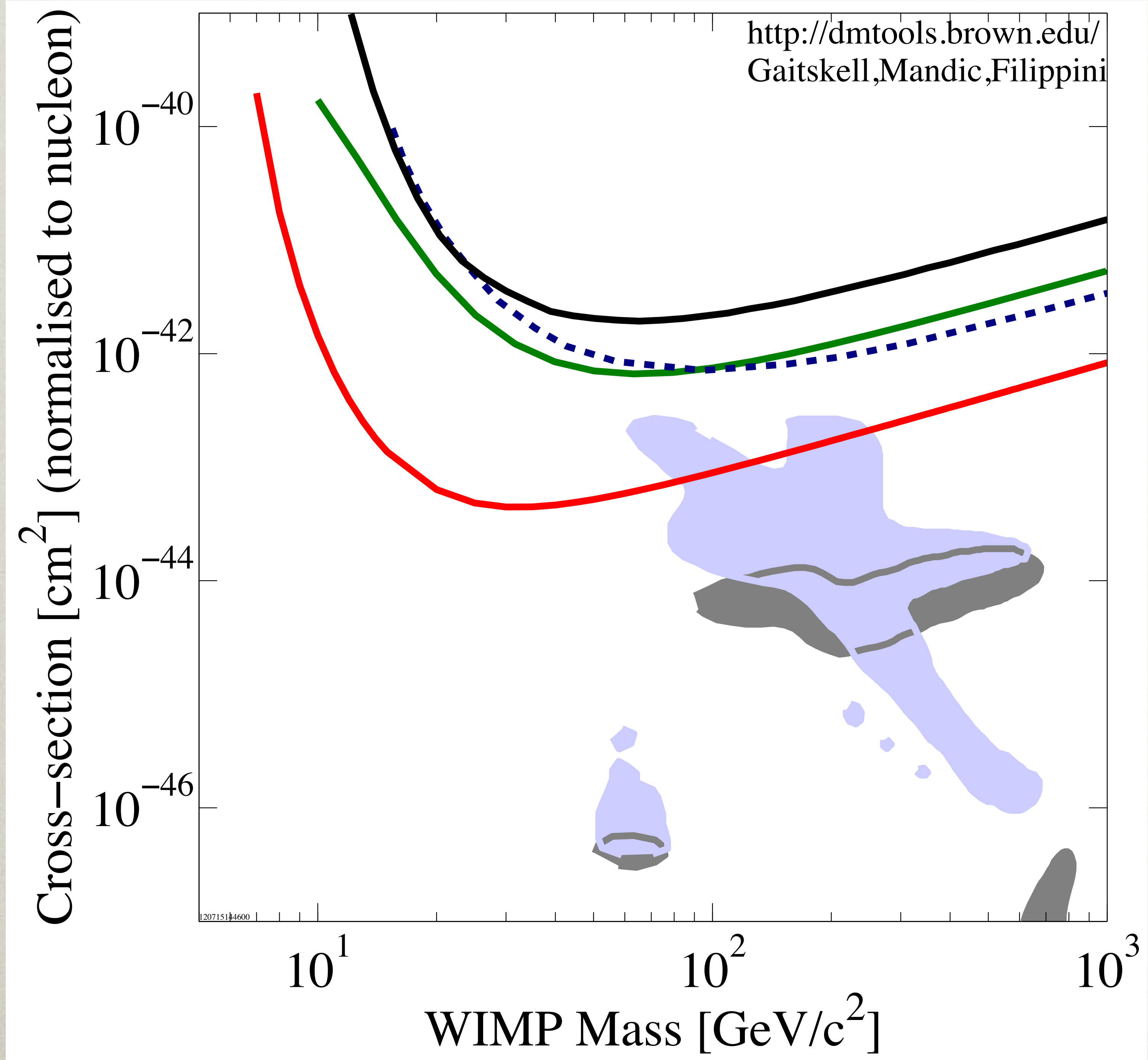
Year 2005

Time-progression of sensitivity



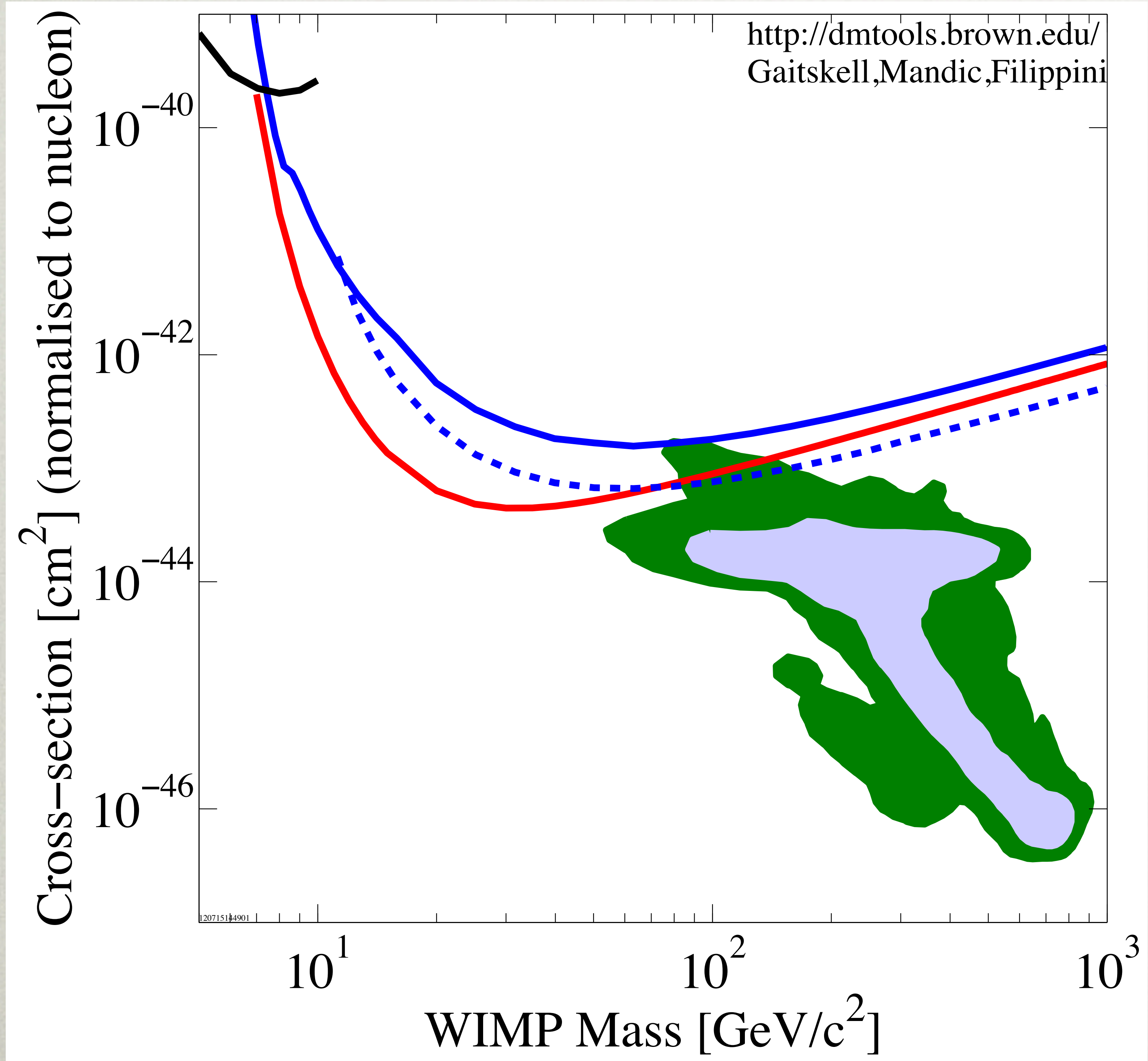
Year 2006

Time-progression of sensitivity



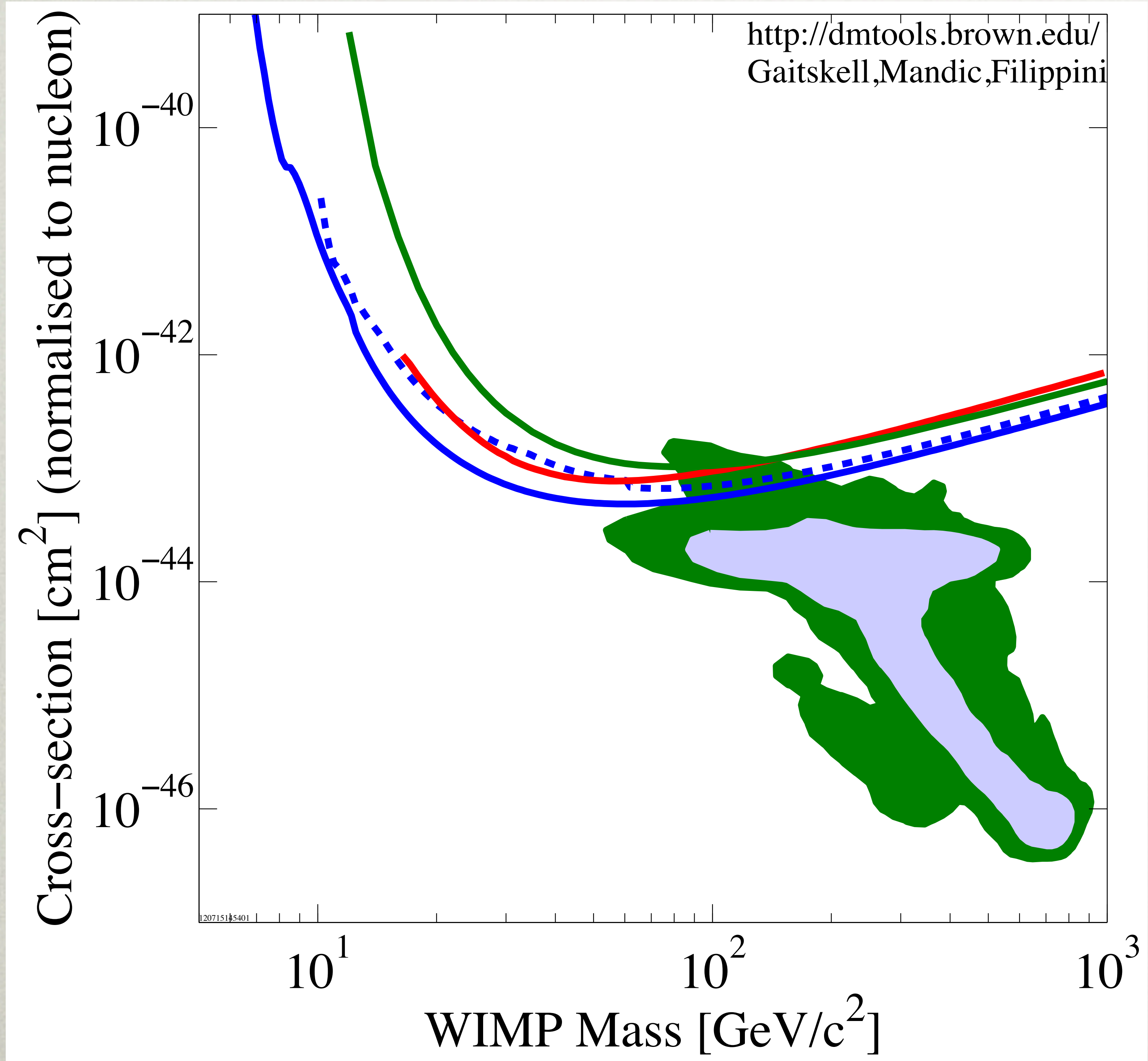
Year 2007

Time-progression of sensitivity



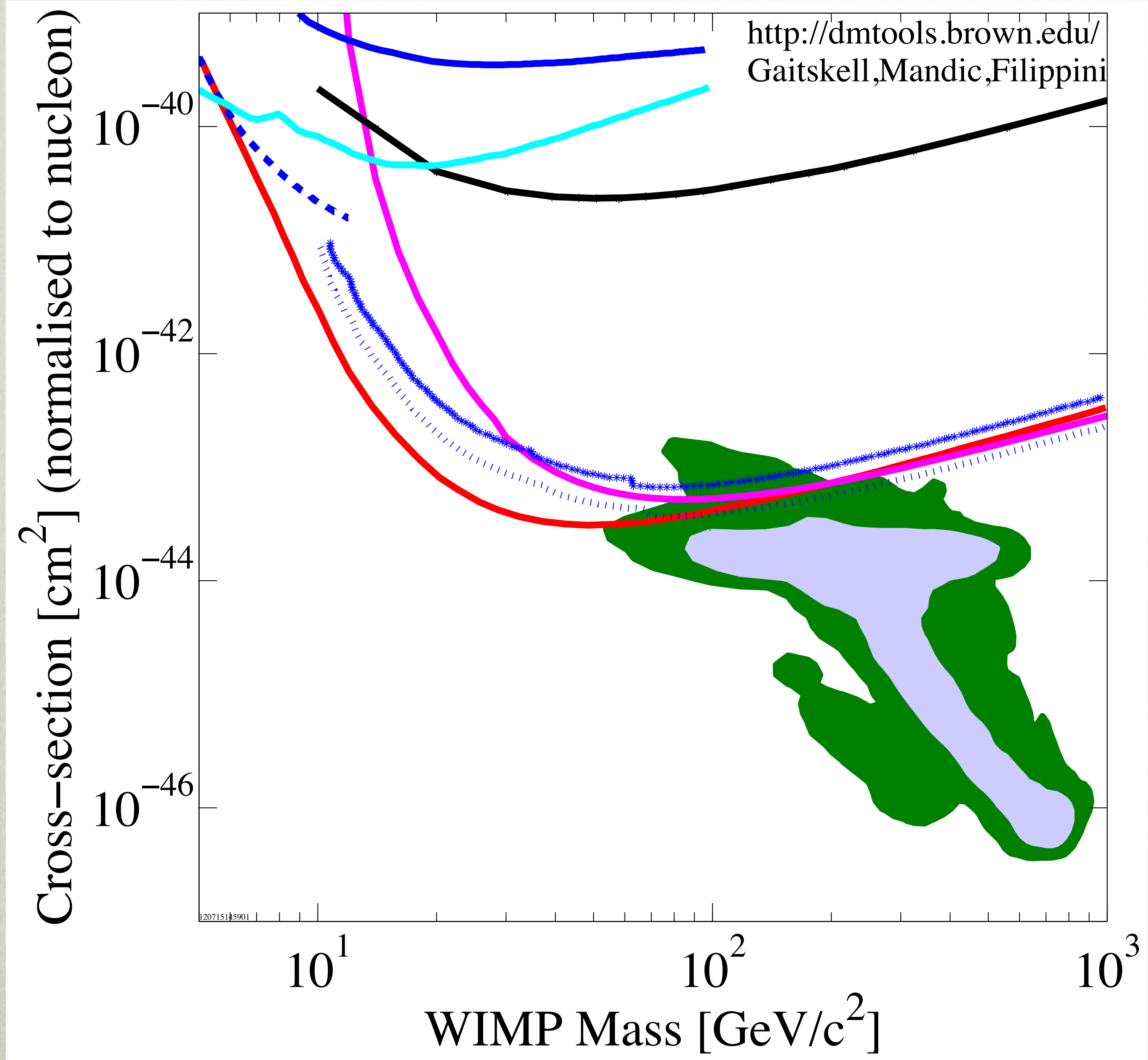
Year 2008

Time-progression of sensitivity



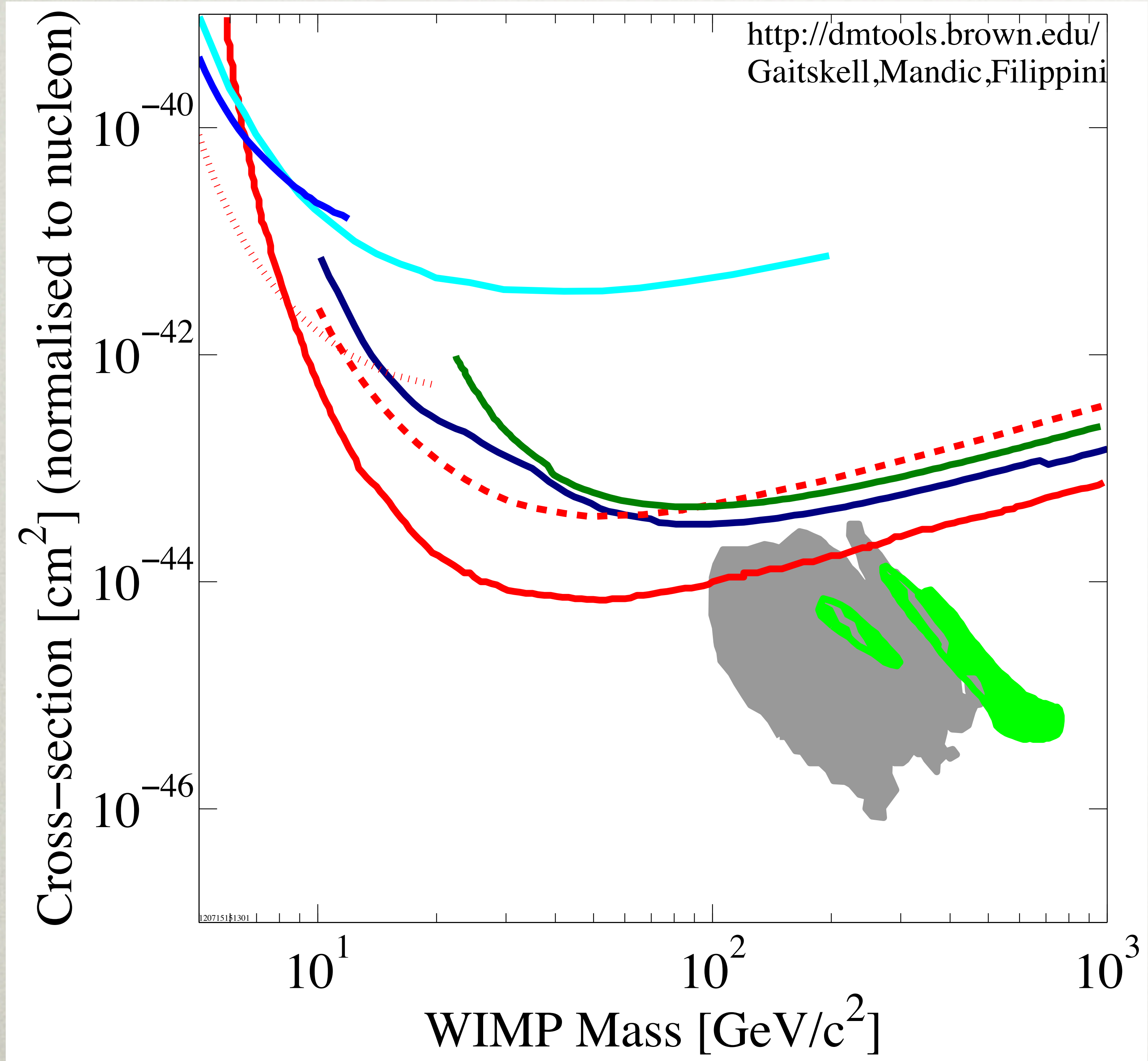
Year 2009

Time-progression of sensitivity



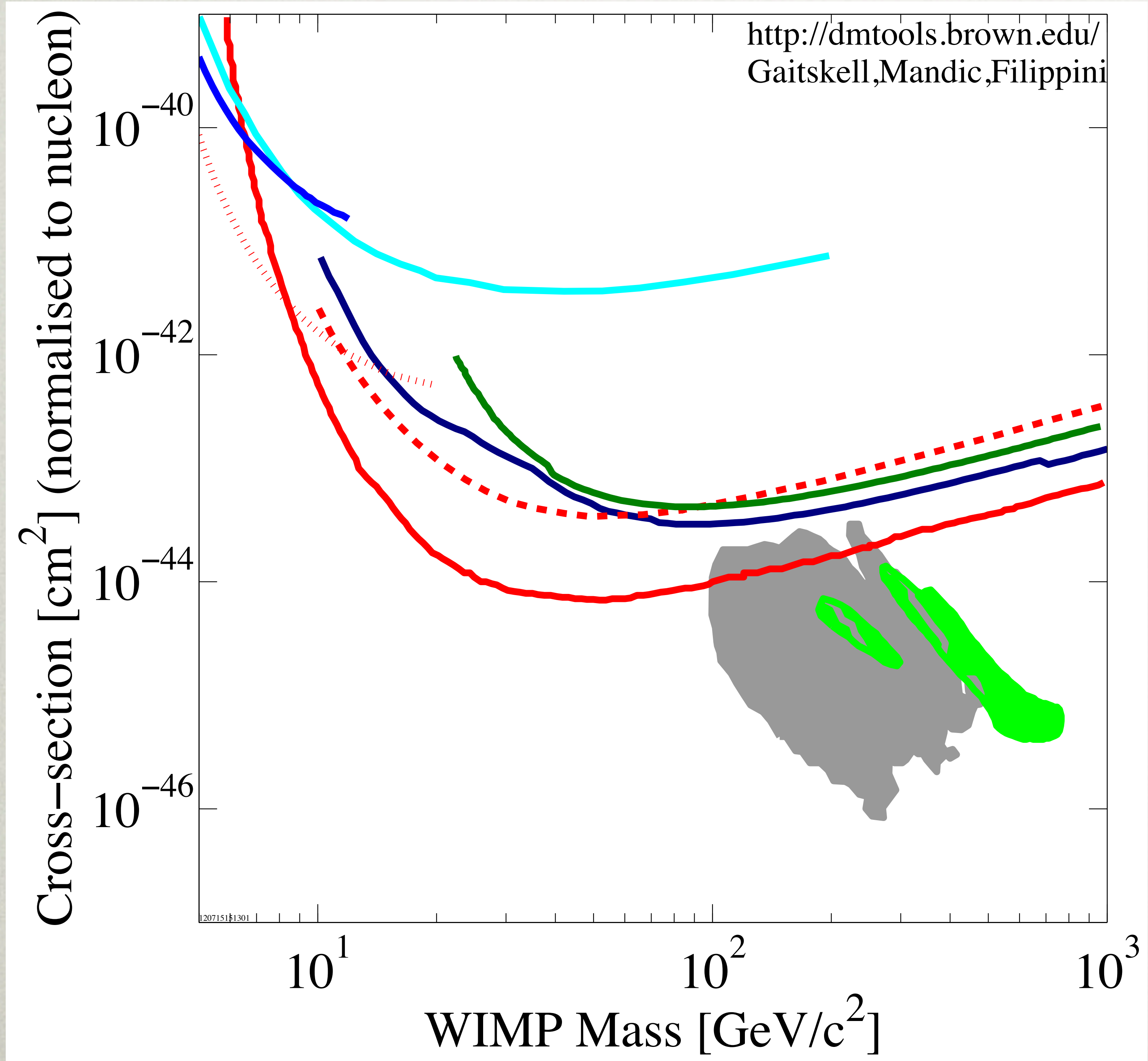
Year 2010

Time-progression of sensitivity



Year 2011

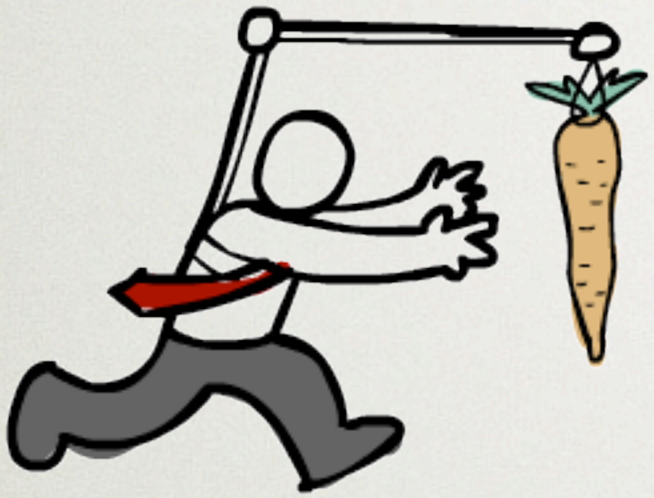
Time-progression of sensitivity



Year 2011

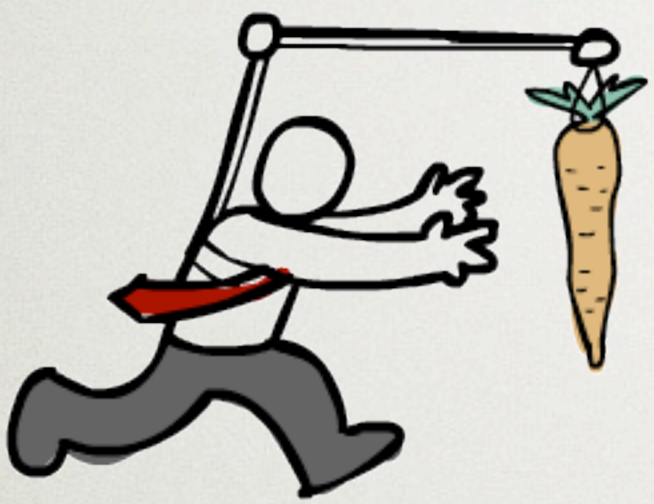
You'll notice that both the experimental limits, AND the theoretical predictions have been falling in this parameter space over the last twelve years

It’s complicated, baby



Searching for WIMPs is a bit like chasing after a moving target...

It’s complicated, baby



Searching for WIMPs is a bit like chasing after a moving target...

~~**Physicists**~~

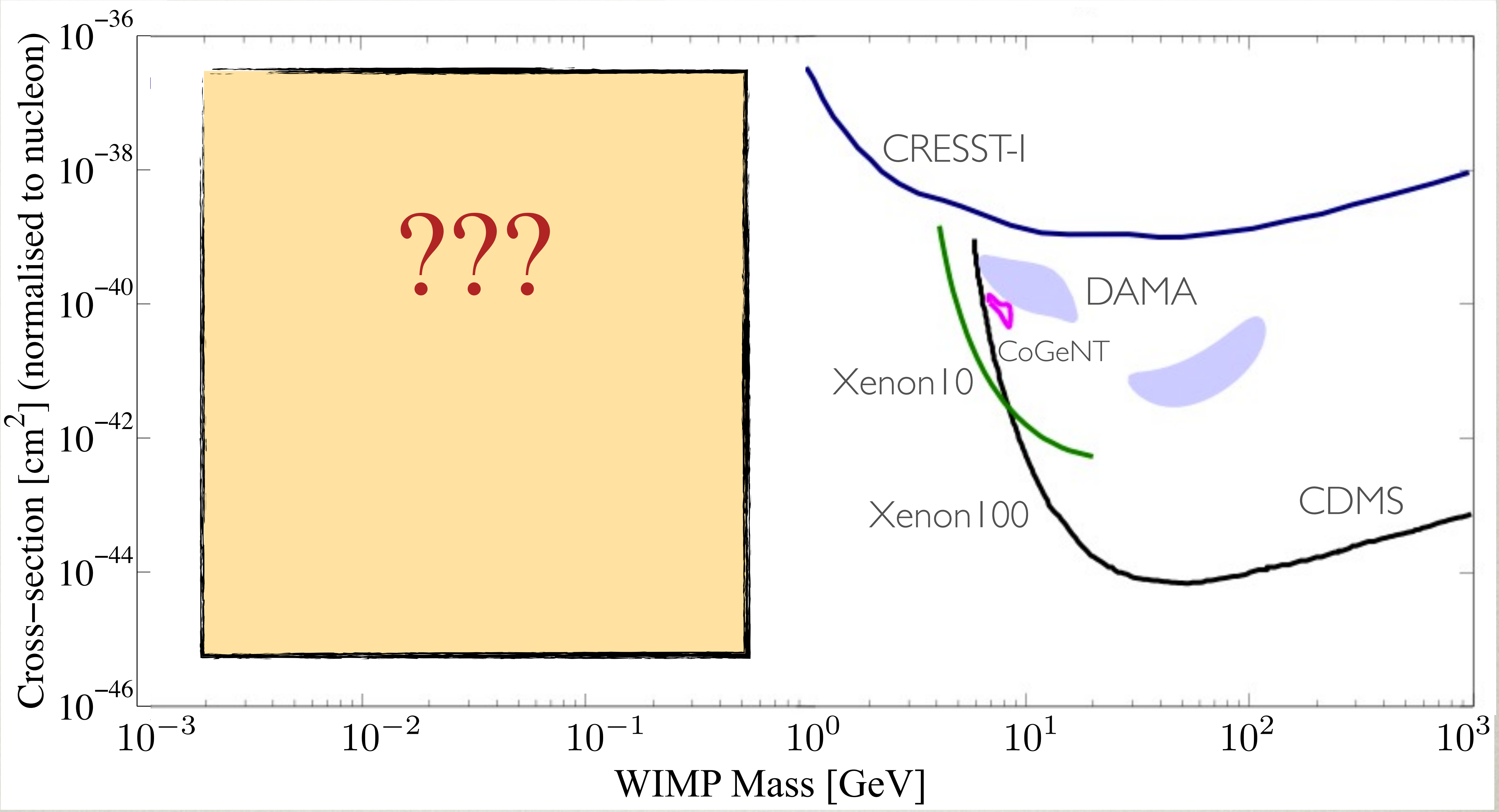
~~Relationship Status — In a relationship with WIMPs~~

~~Anniversary — July 25, 1977~~

Physicists

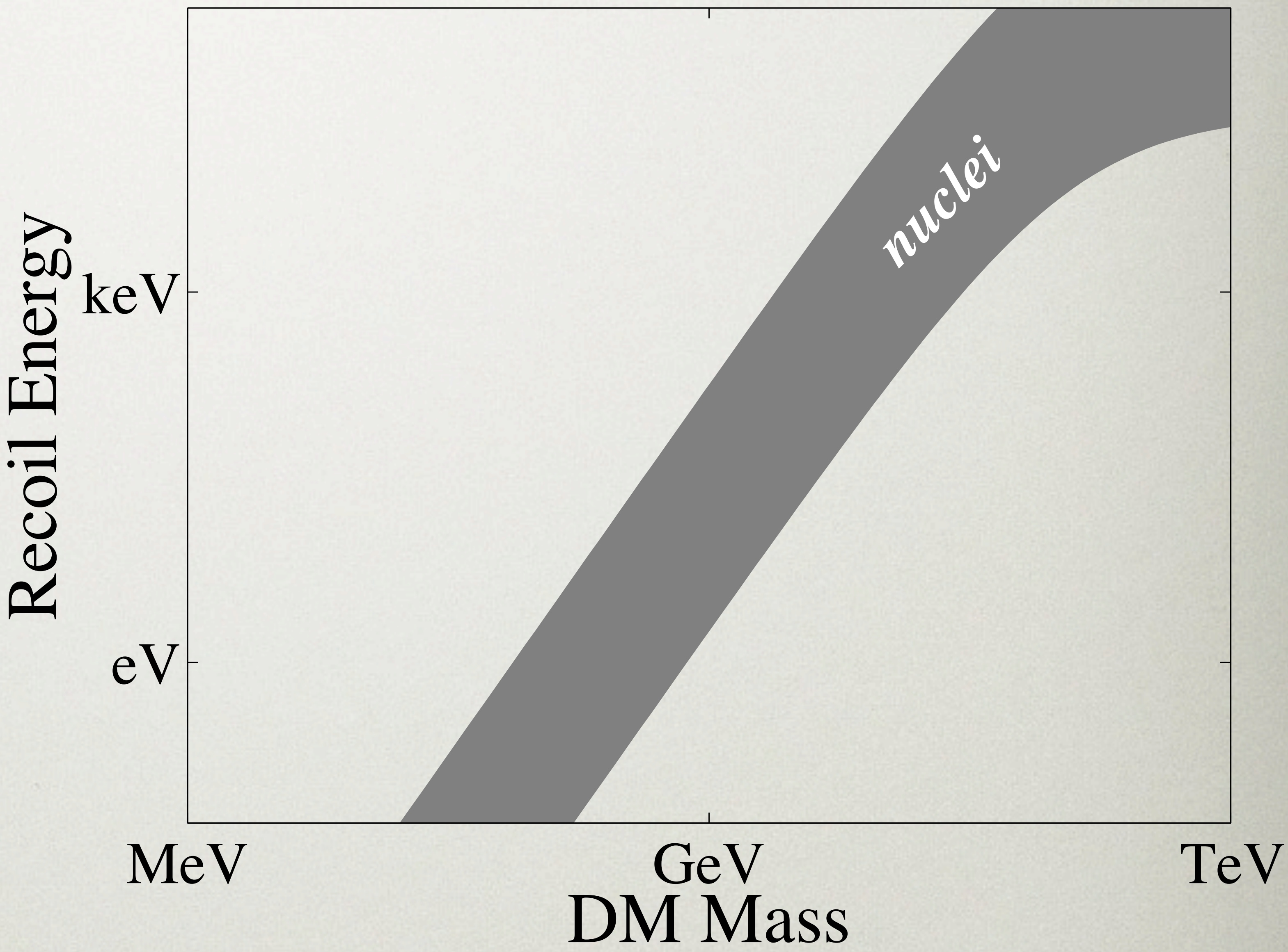
Relationship Status — It’s complicated

Playing the field



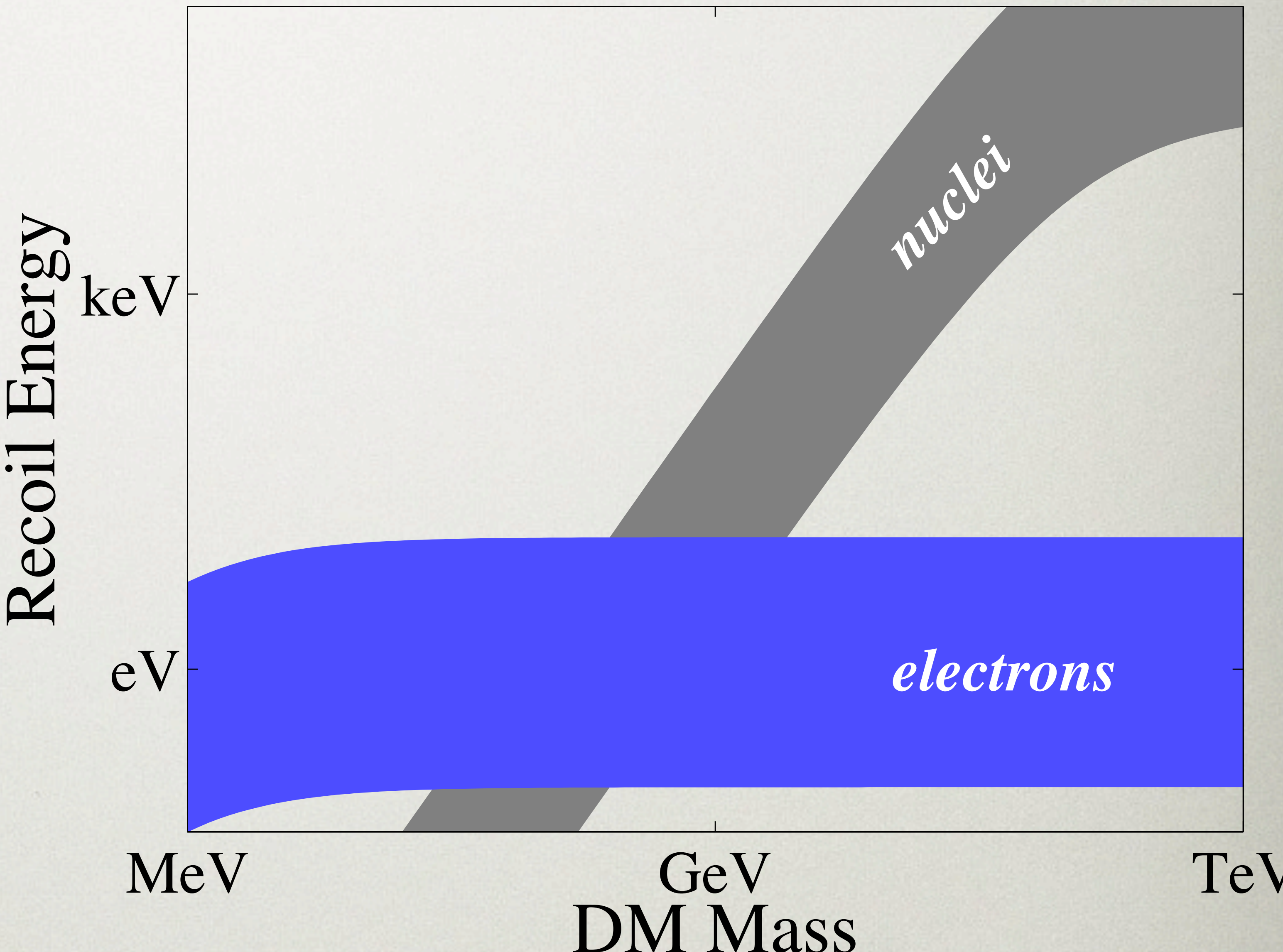
Kinematics, thou art a heartless...

Kinematics simply don't allow for the observation of nuclear recoils from sub-GeV DM scatters



Kinematics, thou art a heartless...

Electronic recoil energies, on the other hand, stay relatively flat for $M_{DM} \gtrsim$ MeV



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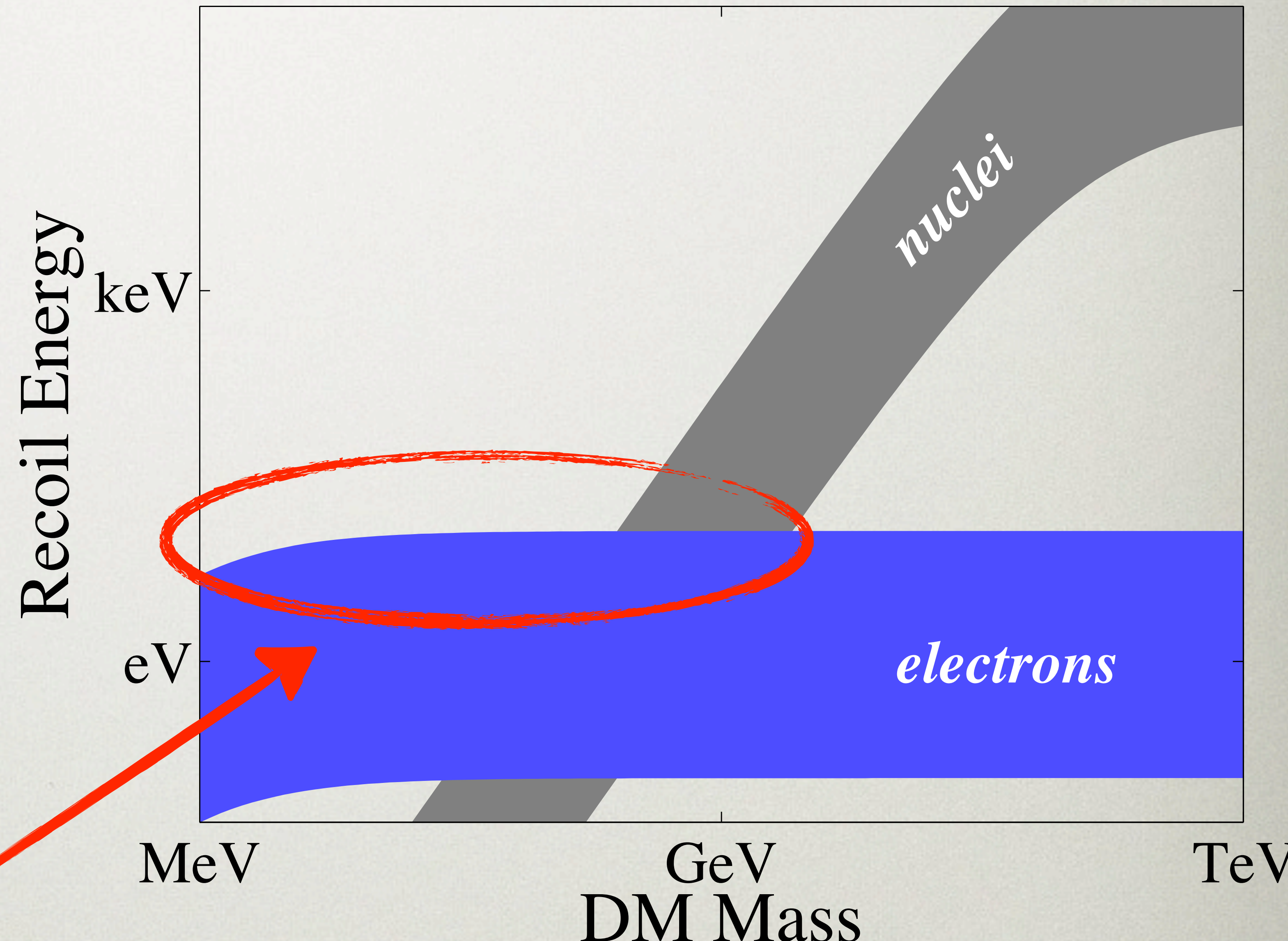
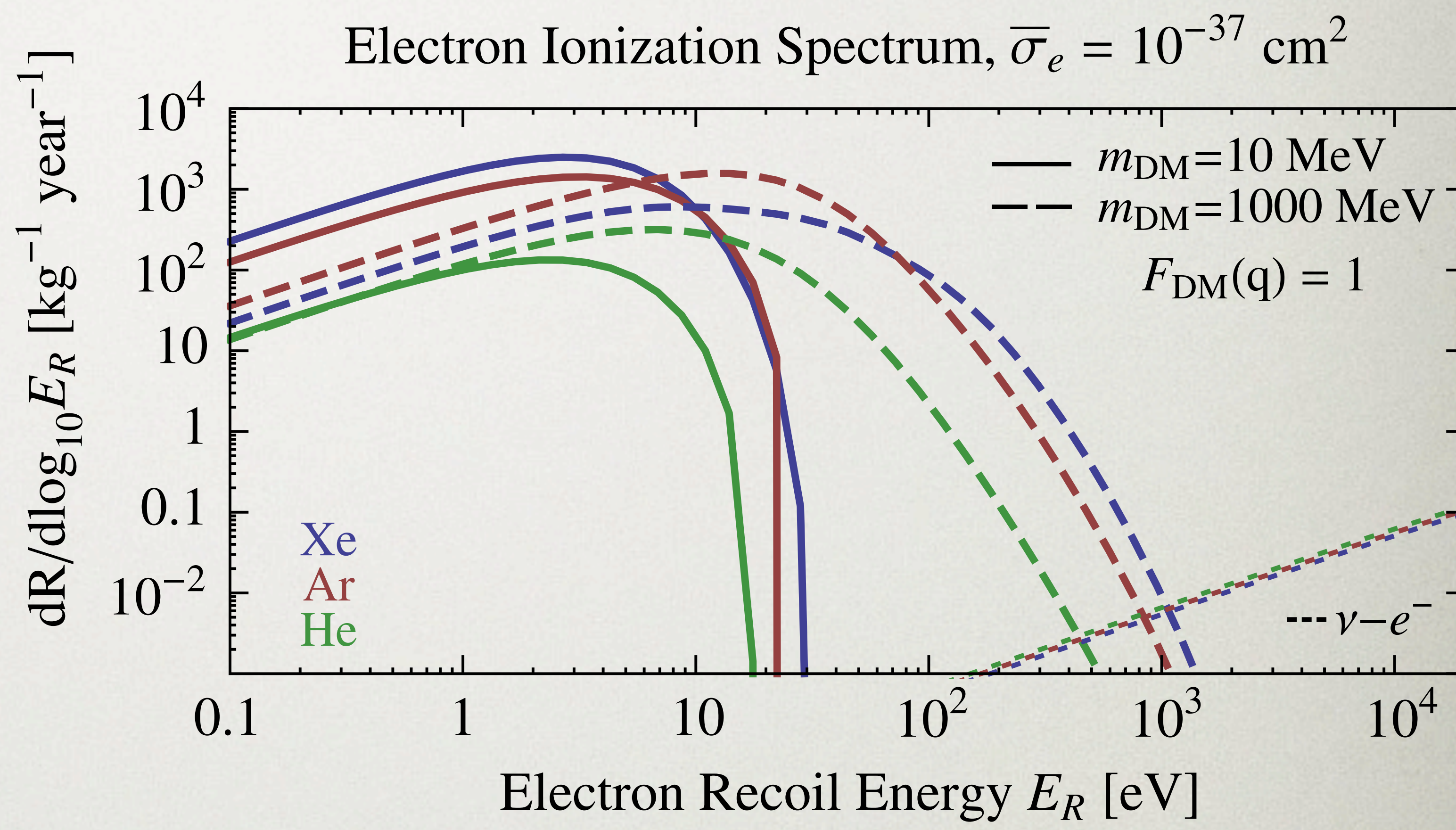


atomic ionization range

Expected energy deposition

The previous slide is very cartoony; a more serious approach considers electron kinetic energy, binding energy, etc., e.g. by R. Essig, J. Mardon, and T. Volansky. We expect electron recoil energies up to ~1 keV.



PHYSICAL REVIEW D **85,** 076007 (2012)

Direct detection of sub-GeV dark matter

Rouven Essig,[1] Jeremy Mardon,[2,3,4] and Tomer Volansky[2,3]

[1]*SLAC National Accelerator Laboratory, Stanford University, Menlo Park, California 94025, USA*
[2]*Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
(Received 2 October 2011; published 9 April 2012)

Direct detection strategies are proposed for dark matter particles with MeV to GeV mass. In this largely unexplored mass range, dark matter scattering with electrons can cause single-electron ionization signals, which are detectable with current technology. Ultraviolet photons, individual ions, and heat are interesting alternative signals. Focusing on ionization, we calculate the expected dark matter scattering rates and estimate the sensitivity of possible experiments. Backgrounds that may be relevant are discussed. Theoretically interesting models may be within reach using existing data and ongoing direct detection experiments. Significant improvements in sensitivity should be possible with dedicated experiments.

Do any experimental results have sensitivity to this sort of signal?

Rewind to Mykonos last year...

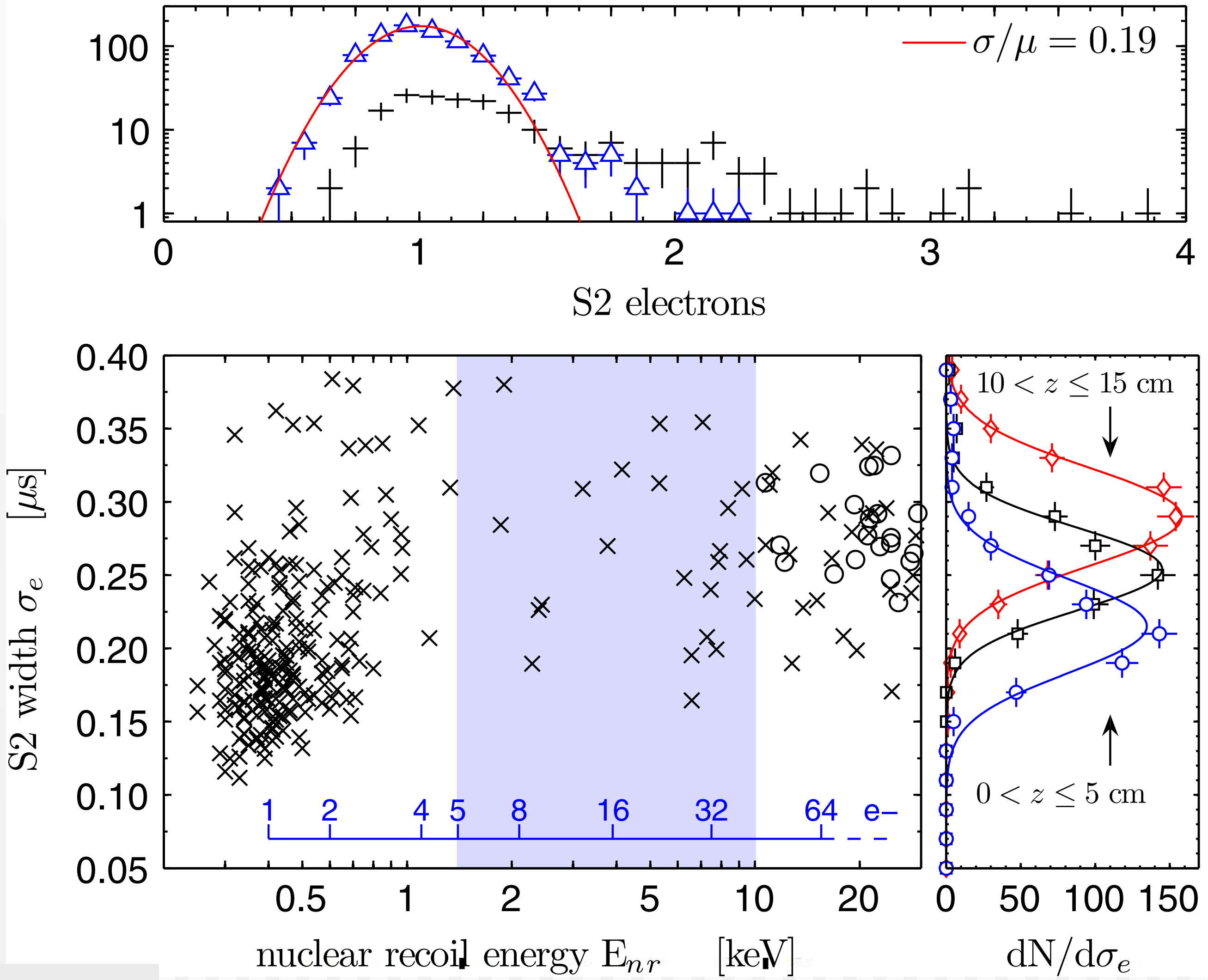
at Patras 2011

Rewind to Mykonos last year...

at Patras 2011

WS2 results

- 1.2 kg fiducial (full z-active region, r<3cm
- 12.5 live days
- 1.4 keV threshold (5 electrons)



J. Angle et al., PRL **107** (2011) 051301 (arXiv:1104.3088)

Signal window (1.4 -10 keVr)

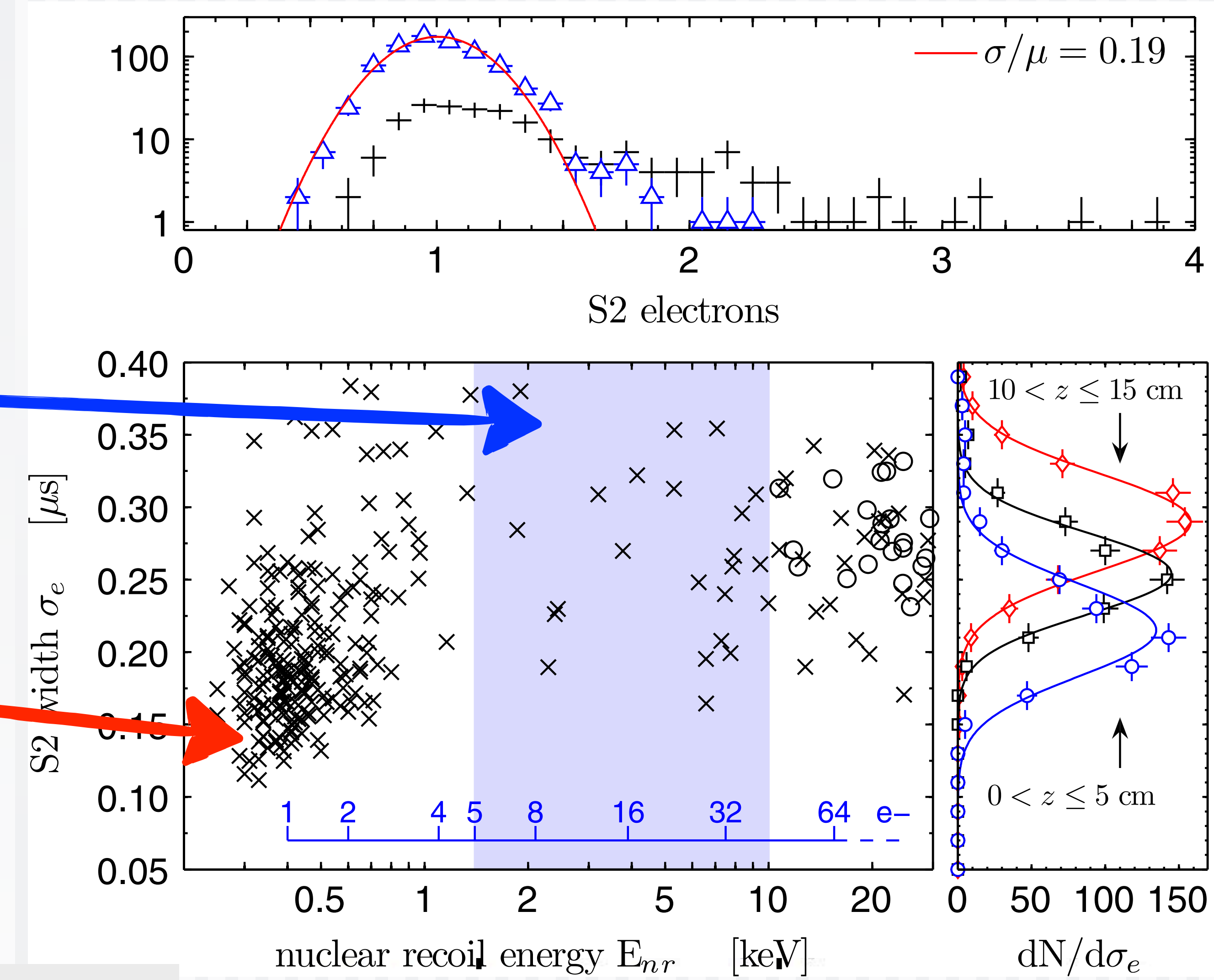
Rewind to Mykonos last year...

at Patras 2011

WS2 results

A search for light WIMPs was performed on the data from the blue band

But notice that the hardware sensitivity extended much further down

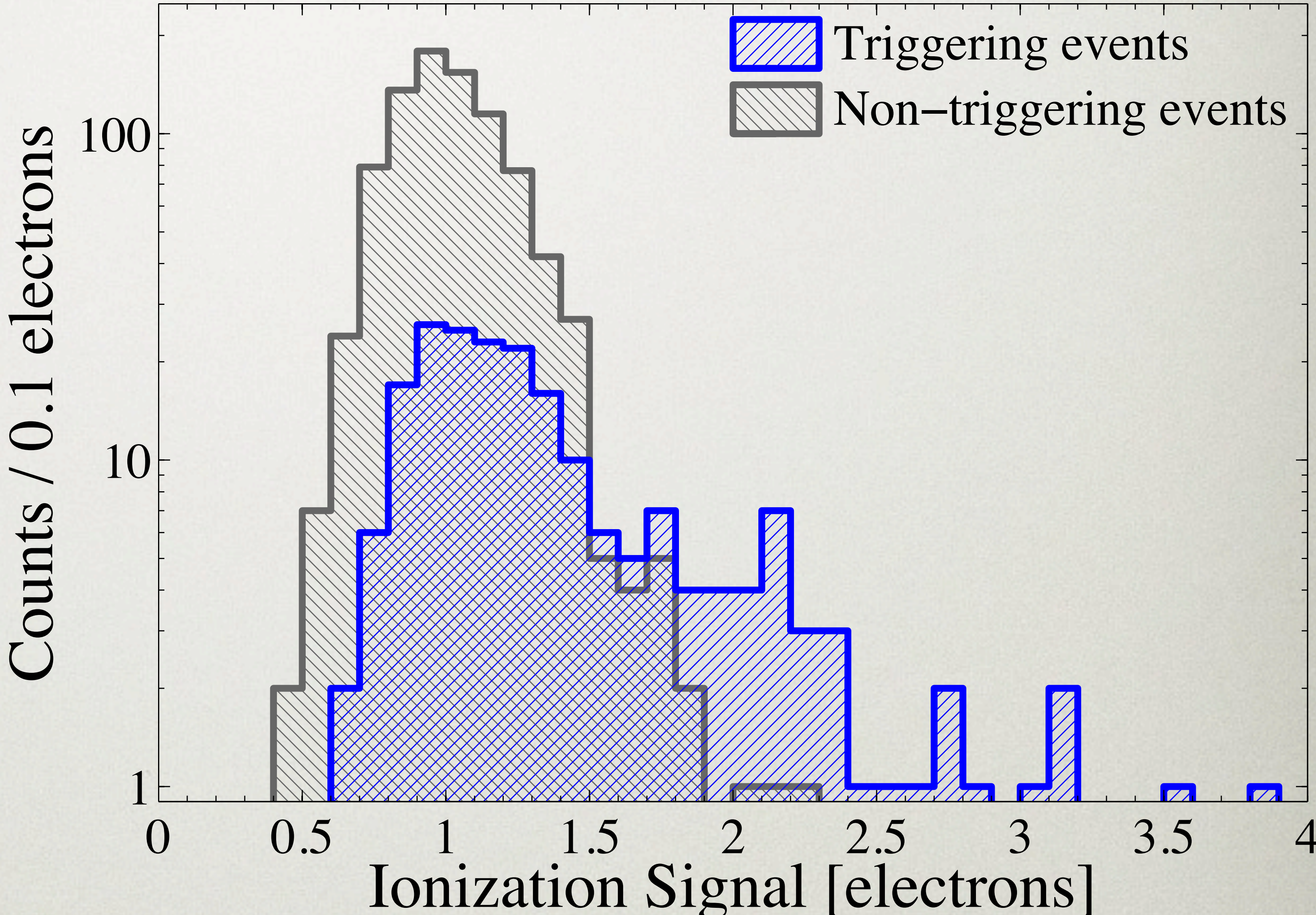


J. Angle et al., PRL **107** (2011) 051301 (arXiv:1104.3088)

Signal window (1.4 -10 keVr)

XENON10's low-E spectrum

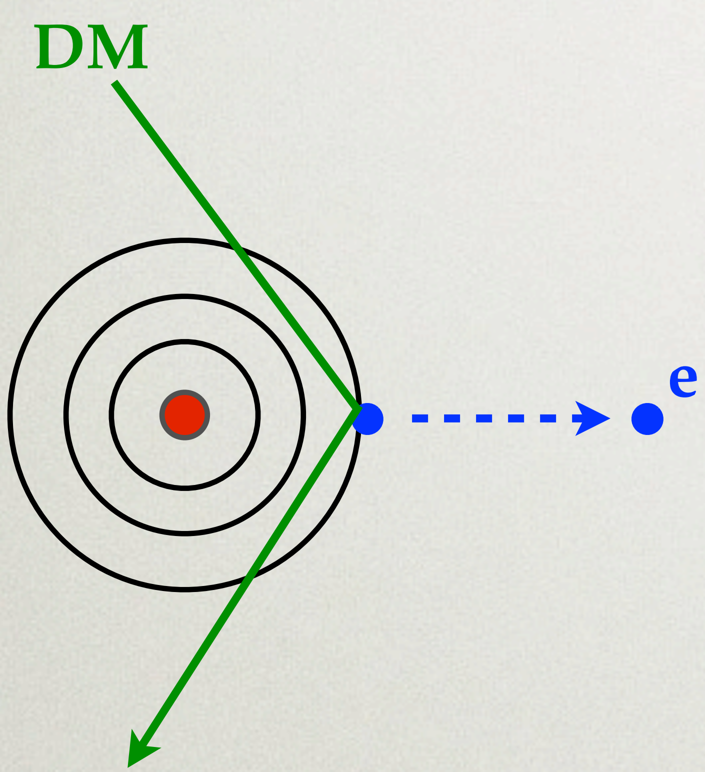
Ionization threshold sensitive to single electrons!



XENON10 spectrum, reproduced from:
J.Angle *et al.*, PRL **107** (2011) 051301

The expected signal

- Step 1: Differential ionization rate

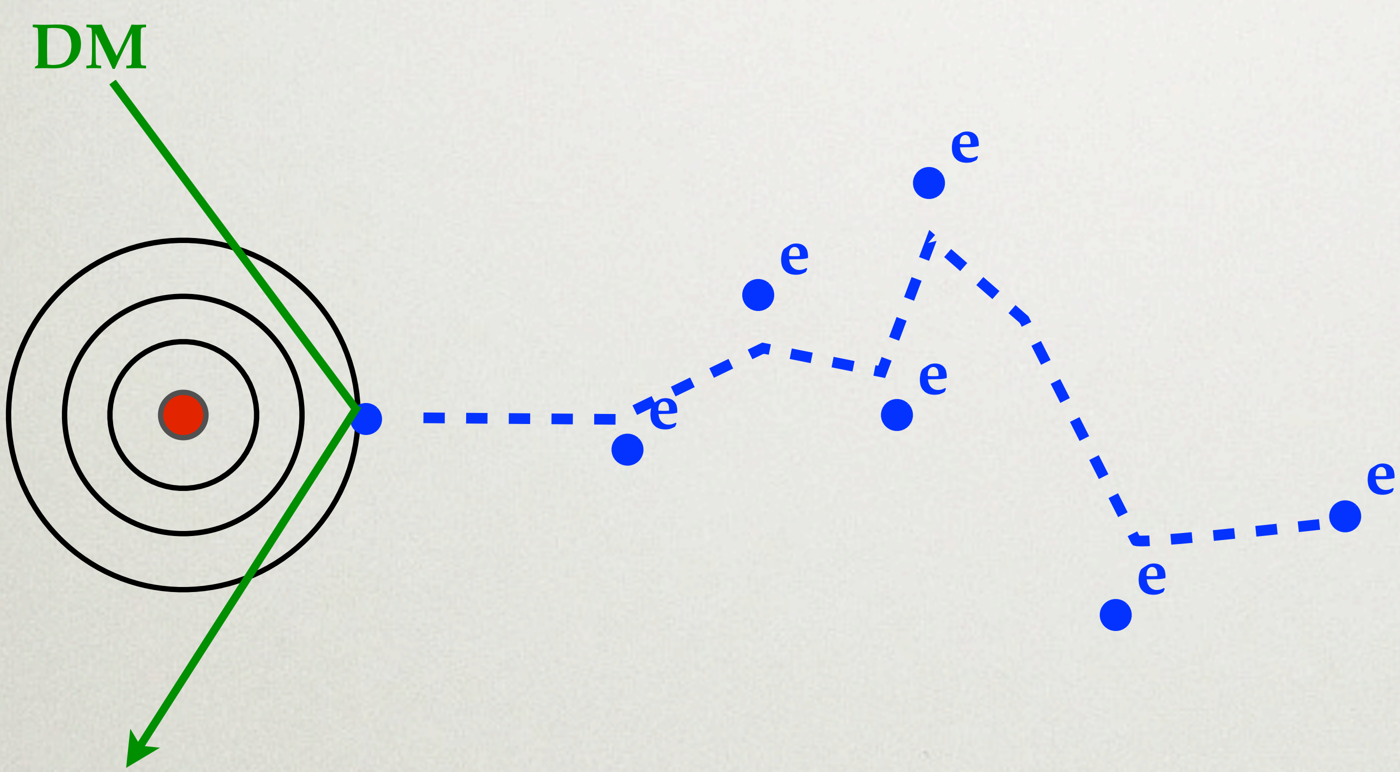


true initial and final electron wavefunctions go into here

$$\frac{dR_{\rm ion}}{d\ln E_{\rm er}} = N_T \frac{\rho_{\rm DM}}{m_{\rm DM}} \sum_{nl} \frac{d\langle \sigma^{nl}_{\rm ion} v\rangle}{d\ln E_{\rm er}}$$

The expected signal

- Step 2: Electron recoil track



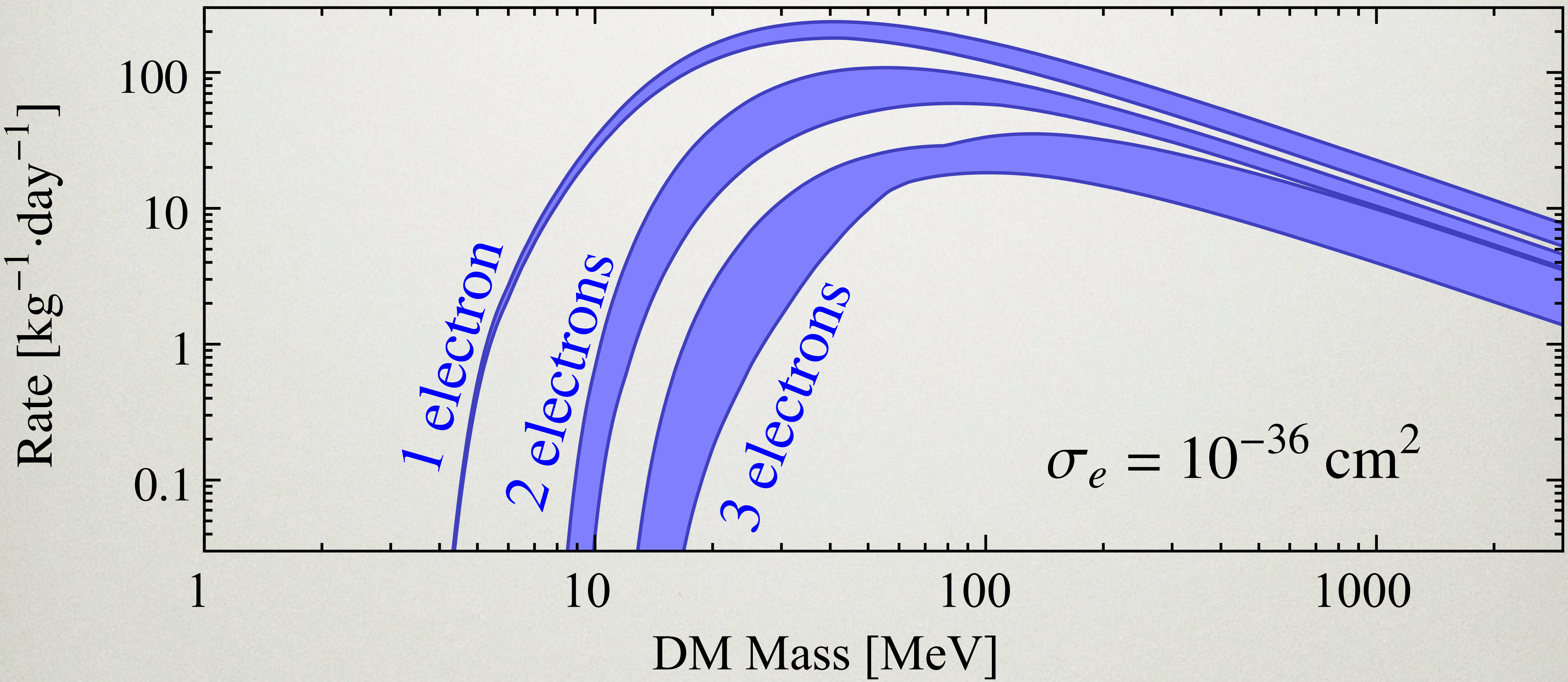
Number of final electrons depends on:

$$W, \ f_R, \ \frac{N_{ex}}{N_i}$$

Varying these values gives us the systematic uncertainty in the expected signal

The expected signal

- Step 3: Rates of 1, 2, and 3 electron events



(bands represent systematic uncertainty in microscopic LXe interaction physics)

XENON10's upper limits

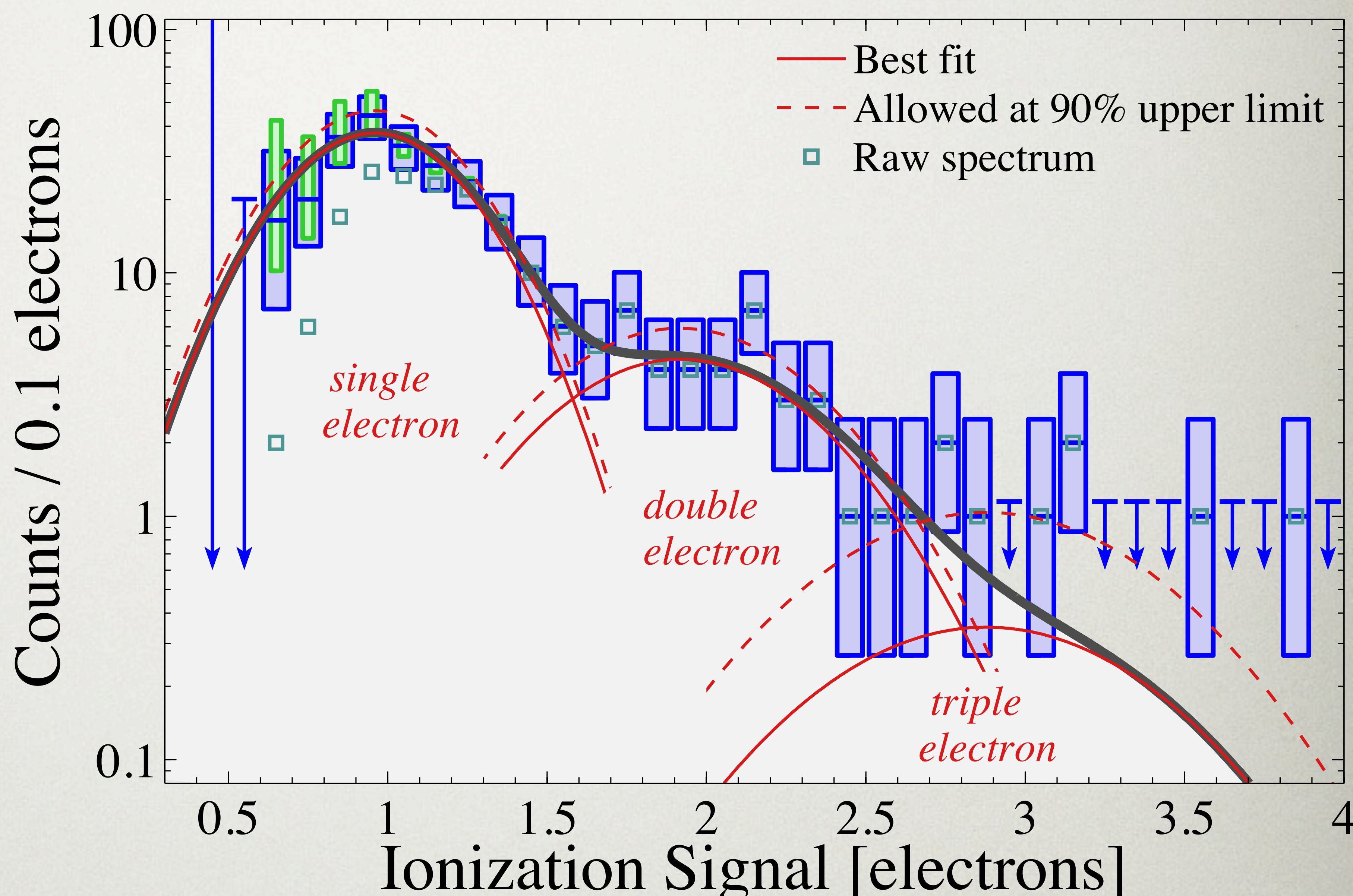
90% C.L. Upper Limits
(cts/kg/day)

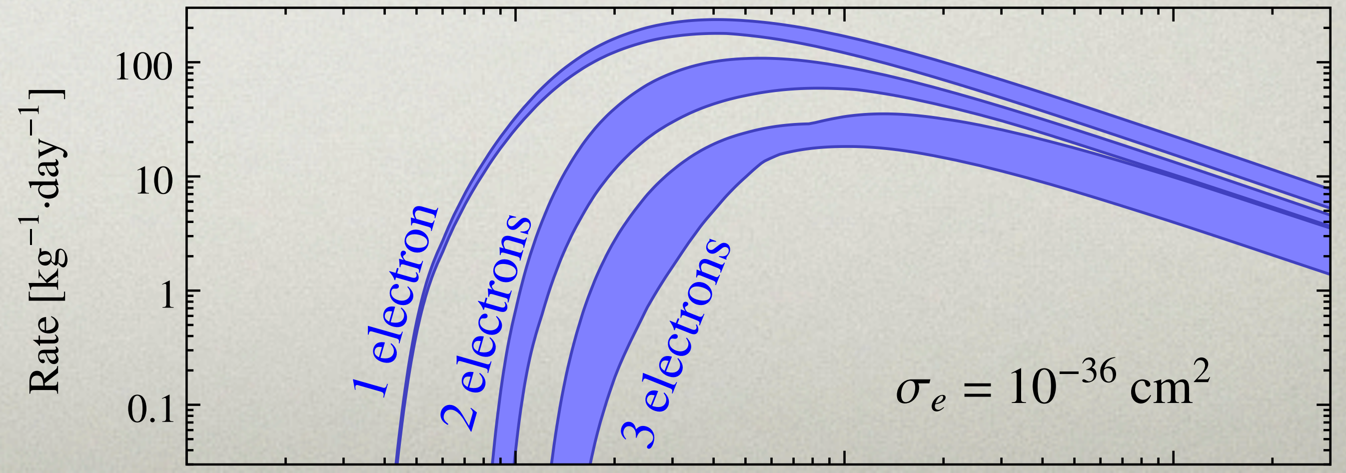
Single e^- < 23.4

Double e^- < 4.23

Triple e^- < 0.90

(no bg-subtraction)



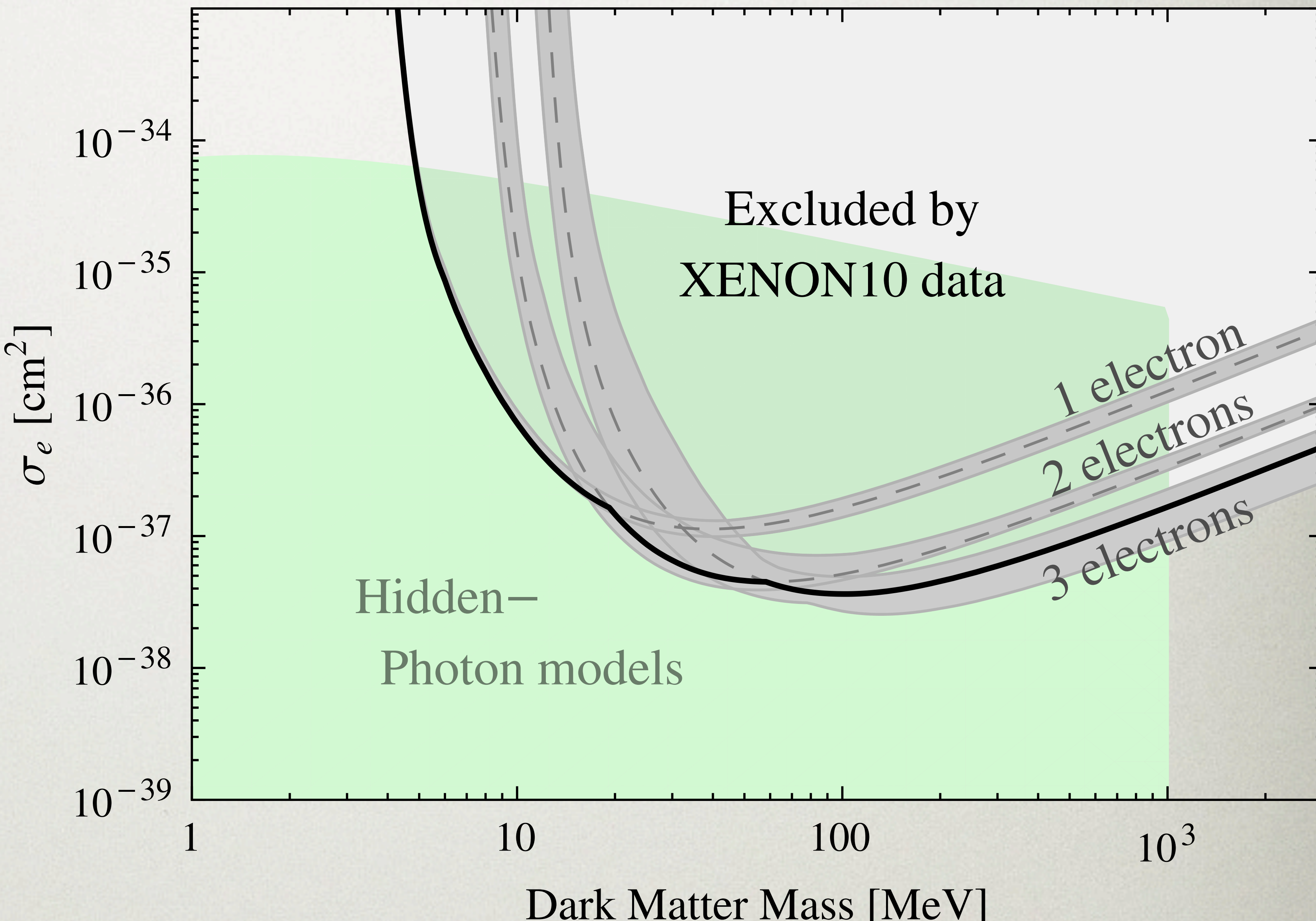


XENON10's upper limits

Already with 15 kg-d we can probe a sizable portion of hidden-photon models, where the DM is a hidden-sector particle that is charged under a U(1)′. Here, $m_{A'} \approx 10$ MeV, $F(q) = 1$

Keep in mind, this is old data with ***only 12.5 live-days***. Imagine what current- and next-generation detectors could achieve (XENON100 just released >200 live-days, with a much larger fiducial volume)

R. Essig, AM, J. Mardon, P. Sorensen, T. Volansky
PRL **109**, 021301 (2012), arXiv:1206.2644



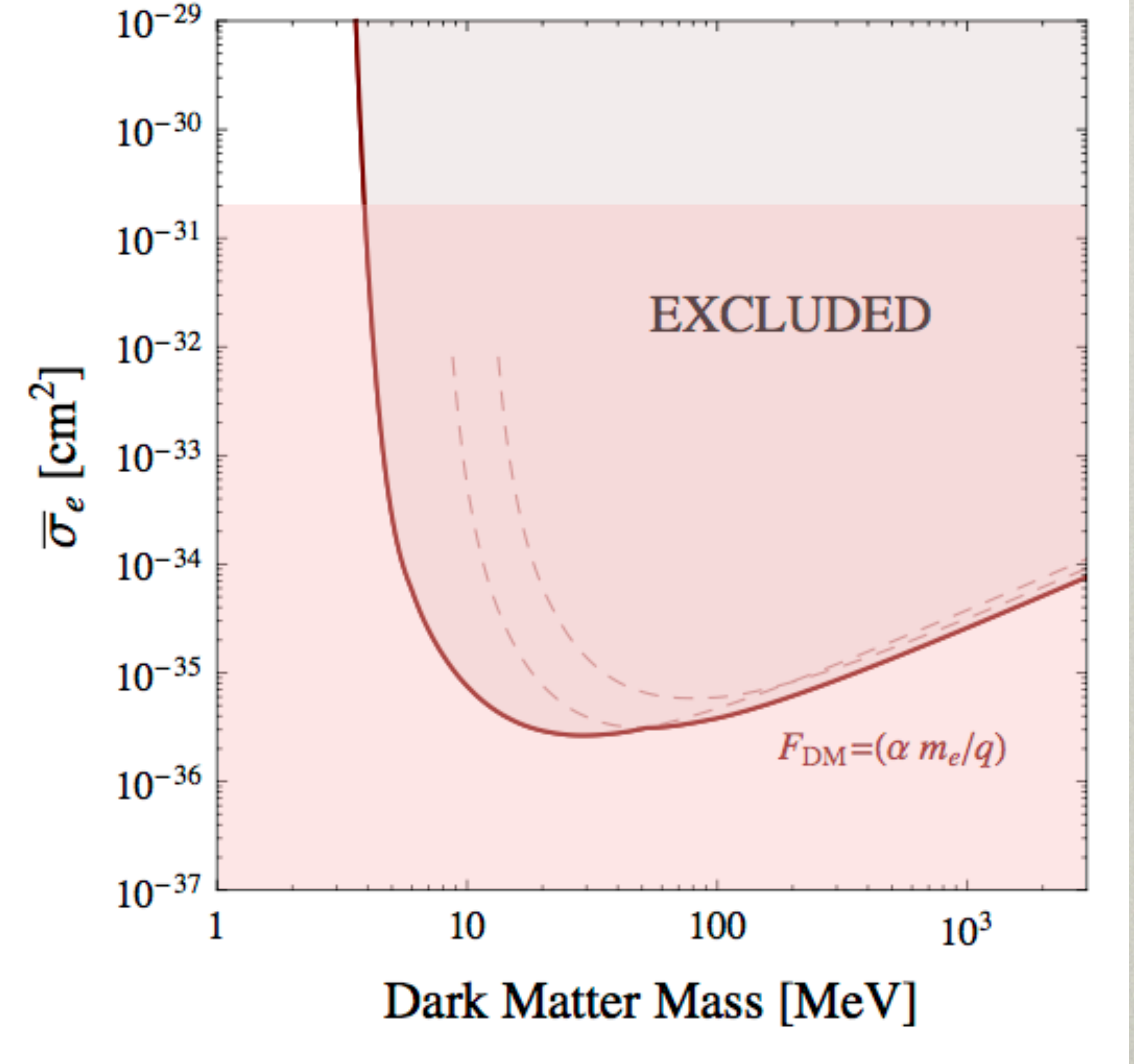
PRL **109,** 021301 (2012) PHYSICAL REVIEW LETTERS week ending 13 JULY 2012

First Direct Detection Limits on Sub-GeV Dark Matter from XENON10

Rouven Essig,[1,2,*] Aaron Manalaysay,[3,†] Jeremy Mardon,[4,‡] Peter Sorensen,[5,§] and Tomer Volansky[6,||]
[1]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, New Jersey, USA*

XENON10’s upper limits

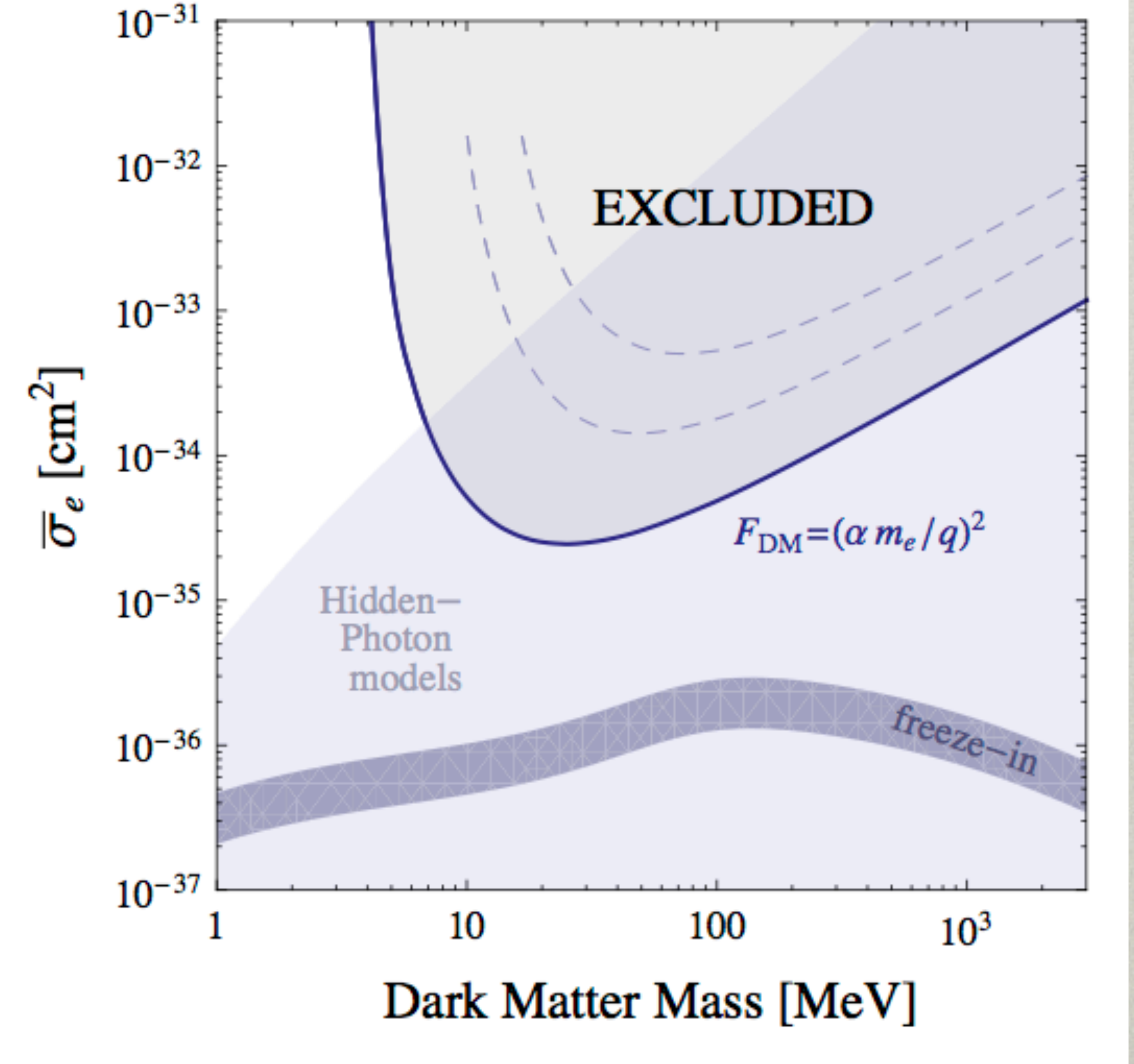
DM with small electric dipole moment, the form factor, $F(q)$, is no longer unity



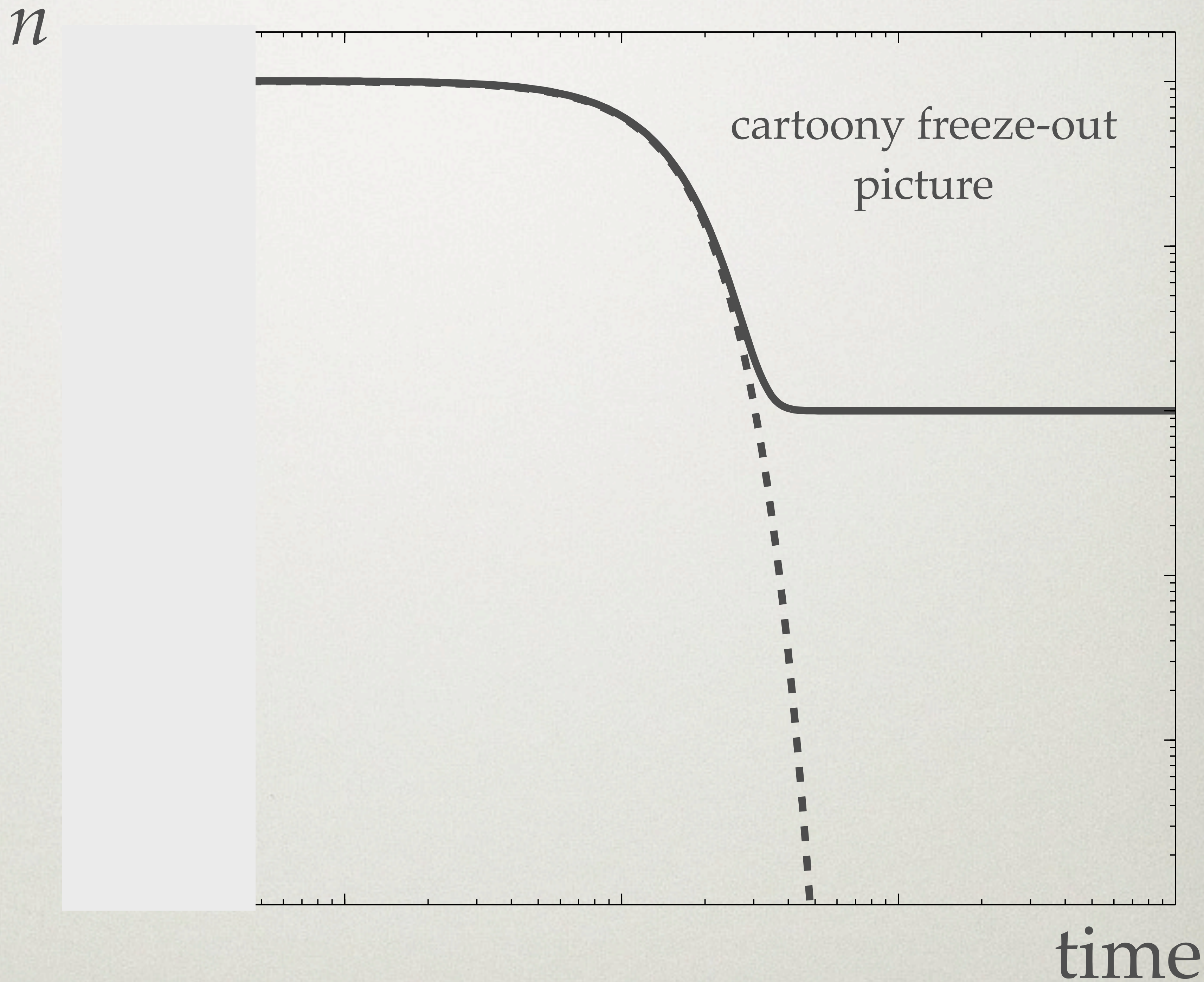
XENON10’s upper limits

For hidden photon models with $m_{A'} \ll$ keV, $F(q)$ scales as $1/q^2$. This scenario includes a very interesting “freeze-in” region of parameter space. Freeze-in is a thermal process that leads to a build-up and relic density of particles in (initially empty) hidden sector. See:

L.J.Hall *et al*.
JHEP**03** (2010) 080

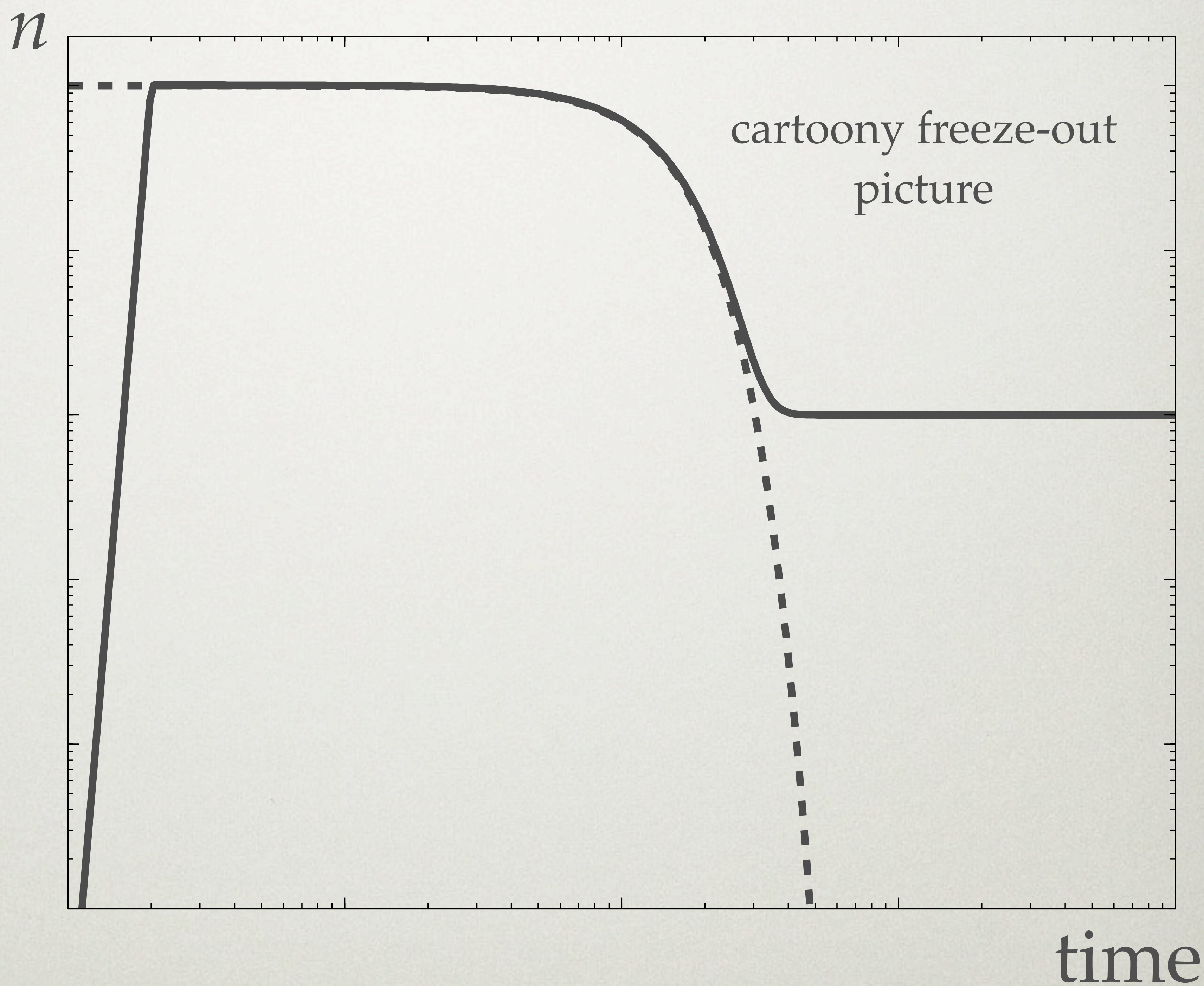


Freeze-in: the other thermal prod

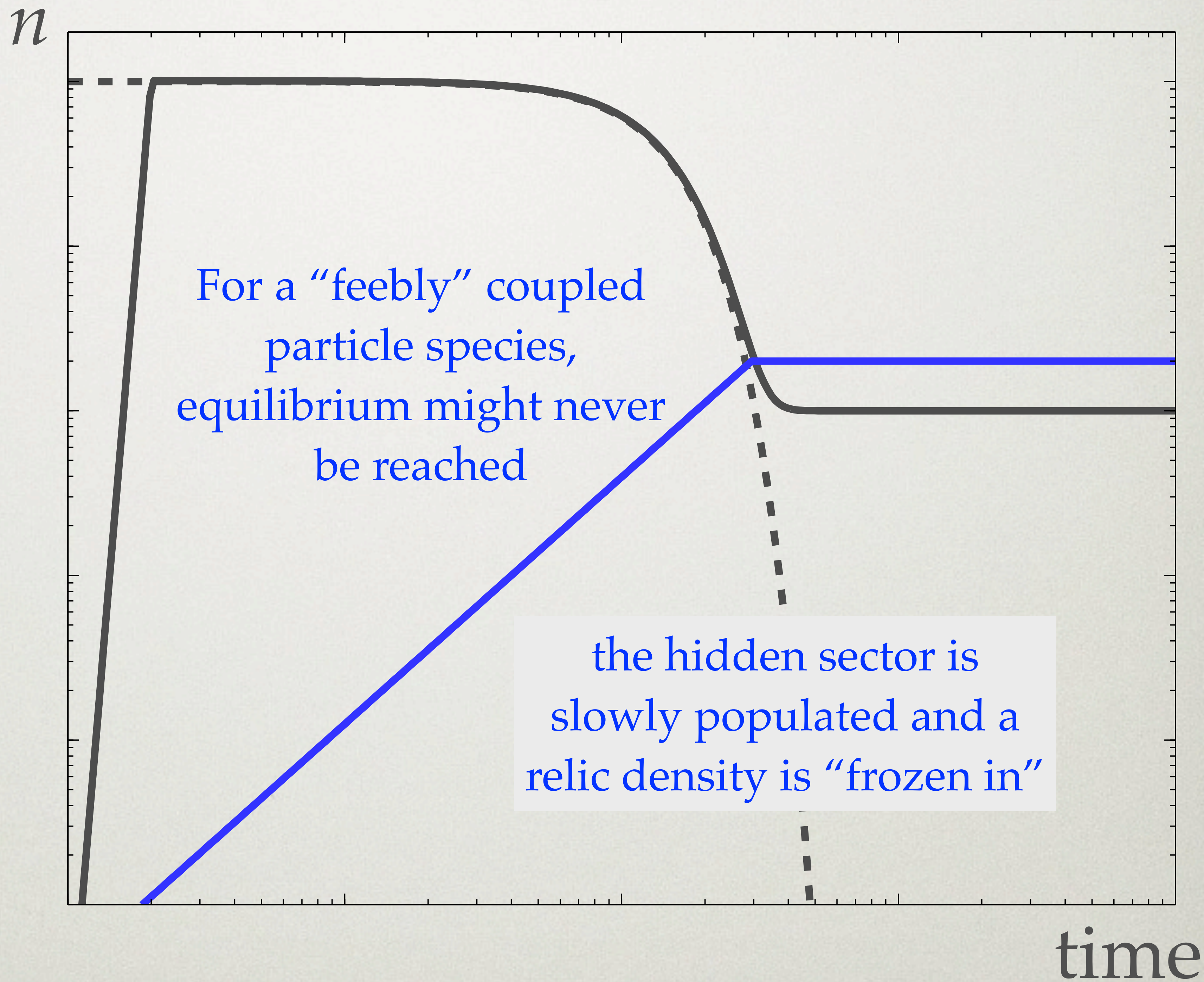


Freeze-in: the other thermal prod

particle χ must first reach equilibrium

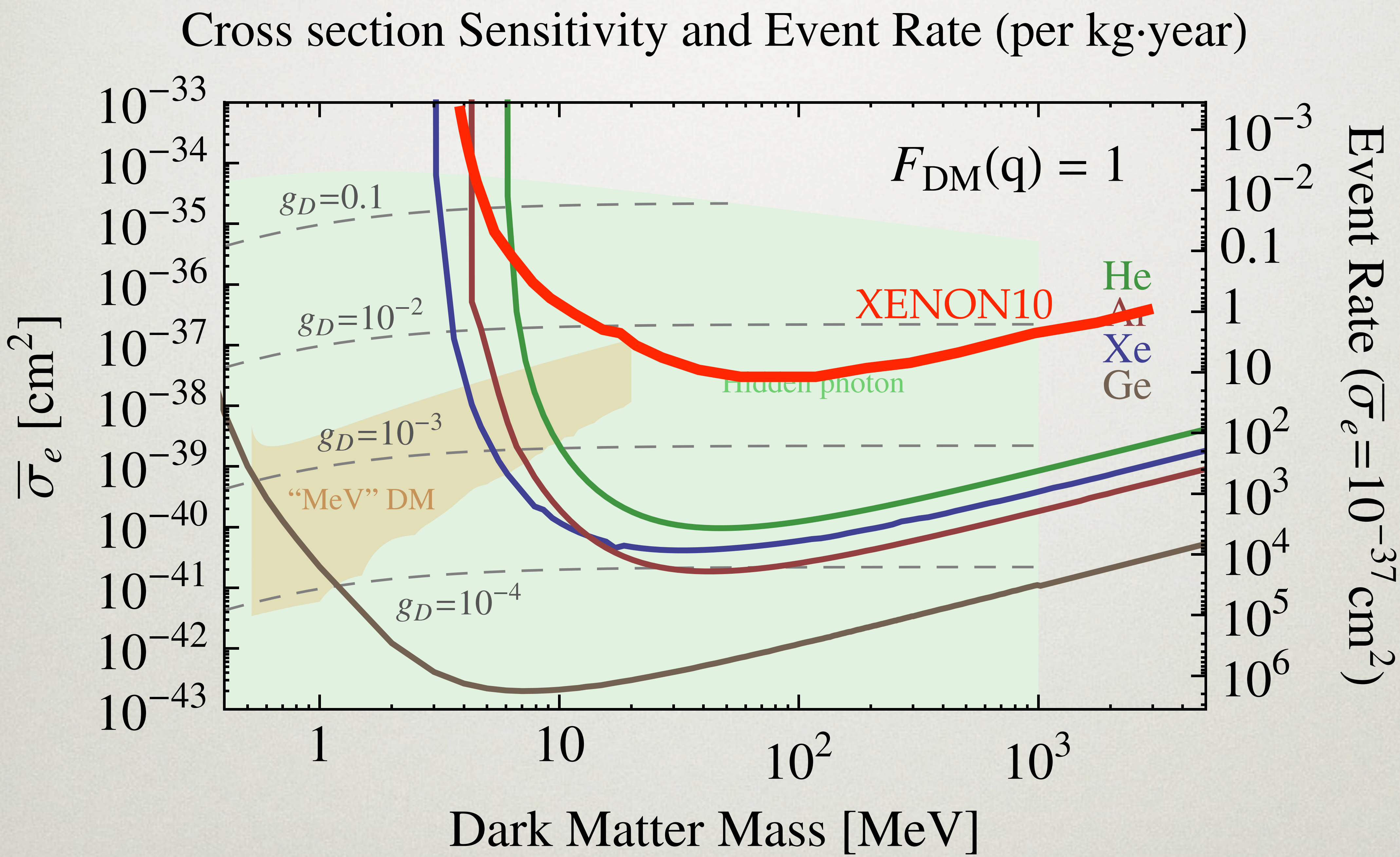


Freeze-in: the other thermal prod



L.J.Hall *et al.*
JHEP**03** (2010) 080

Looking to the future



Summary

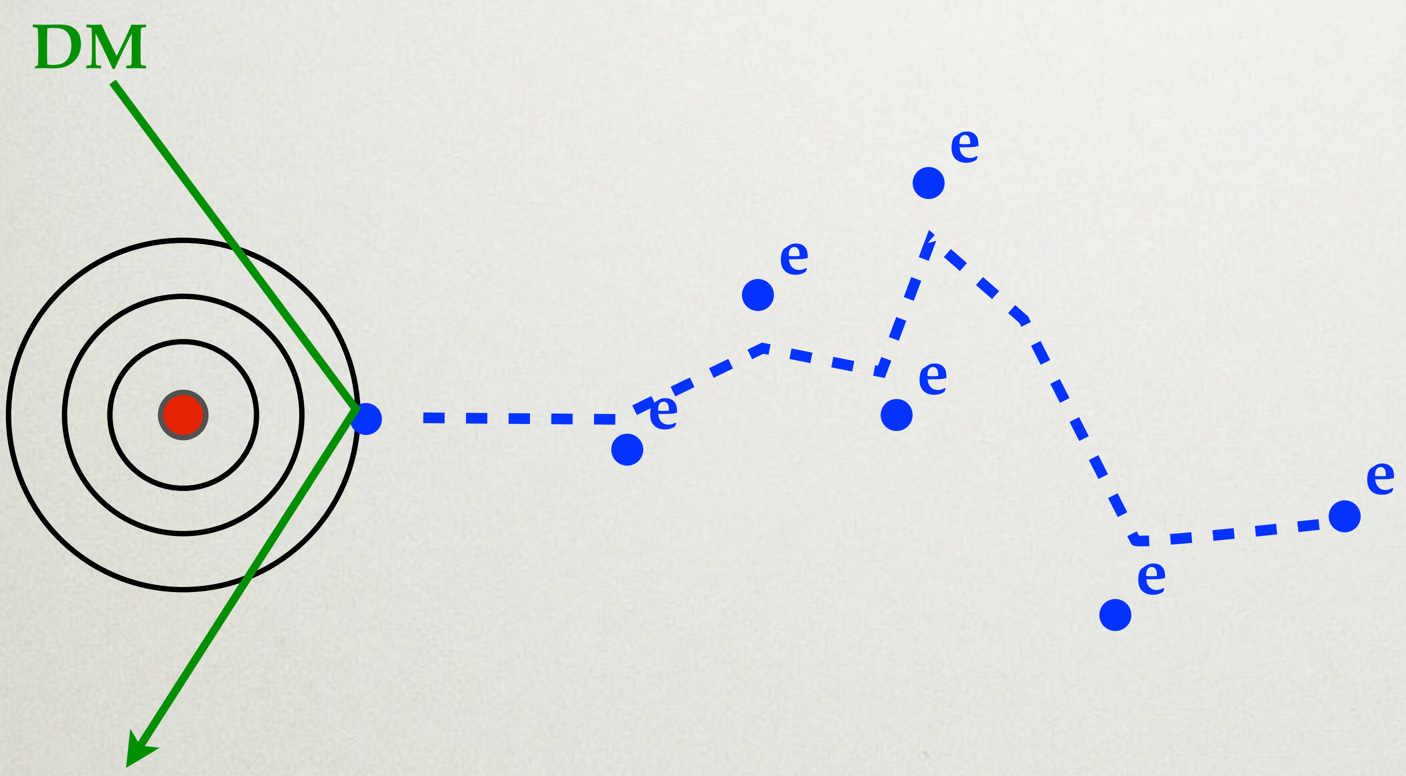
- Sub-GeV particles cannot be detected via nuclear recoils, but are accessible with electronic recoils
- XENON10 data, with a sensitivity to single electrons, can probe many models with sub-GeV DM that feebly couples to electrons
- The XENON10 dataset is a successful proof-of-principle that canonical WIMP search experiments can also achieve sensitivity to sub-GeV DM masses.
- Freeze-out is not the only thermal production mechanism. A feebly coupled hidden sector can also be populated by freeze-in.

Fin

Extras

The expected signal

- Step 2: Electron recoil track



Number of final electrons depends on:

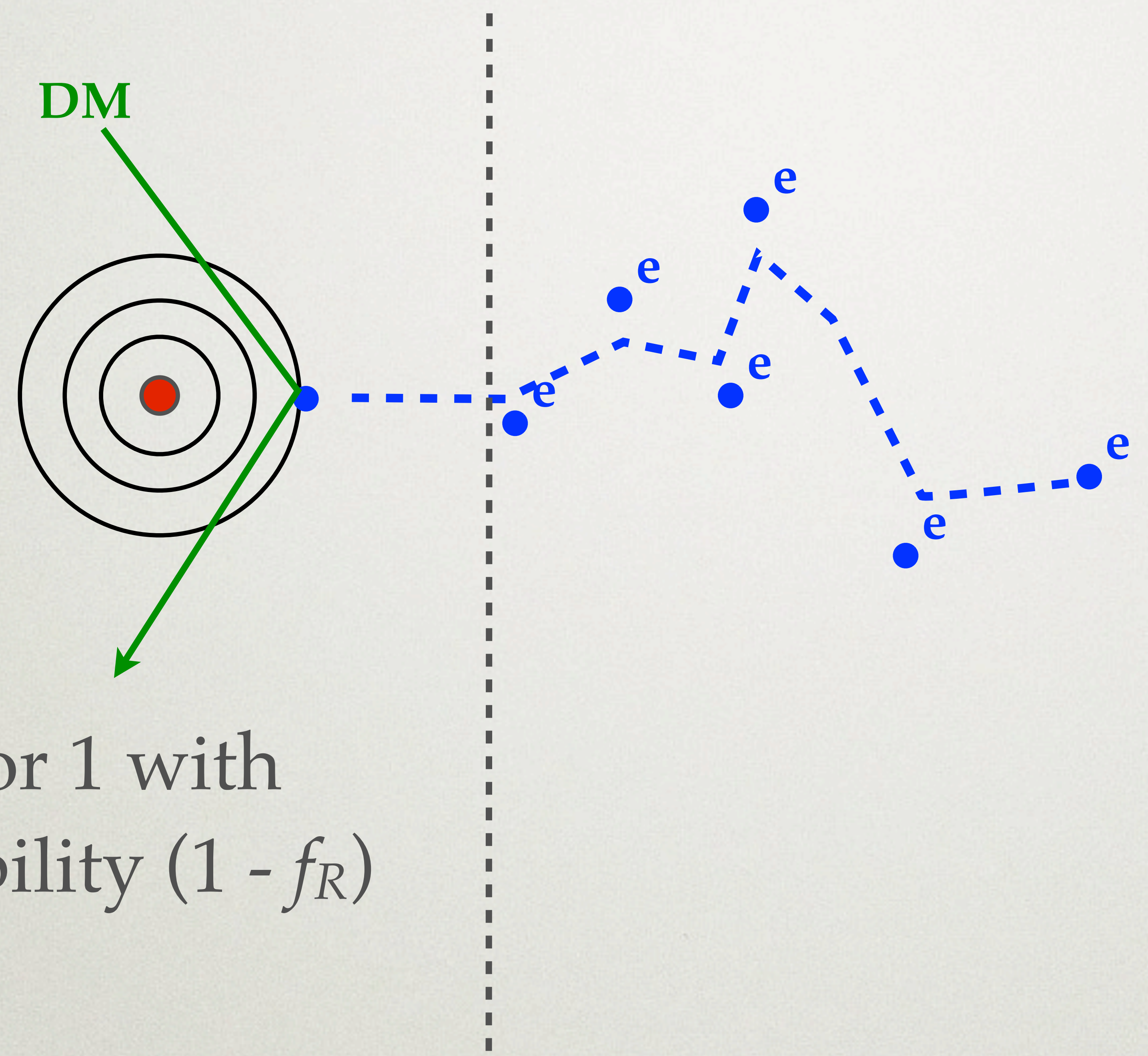
$$W,\ f_R,\ \frac{N_{ex}}{N_i}$$

Varying these values gives us the systematic uncertainty in the expected signal

Tracing the recoiling electron

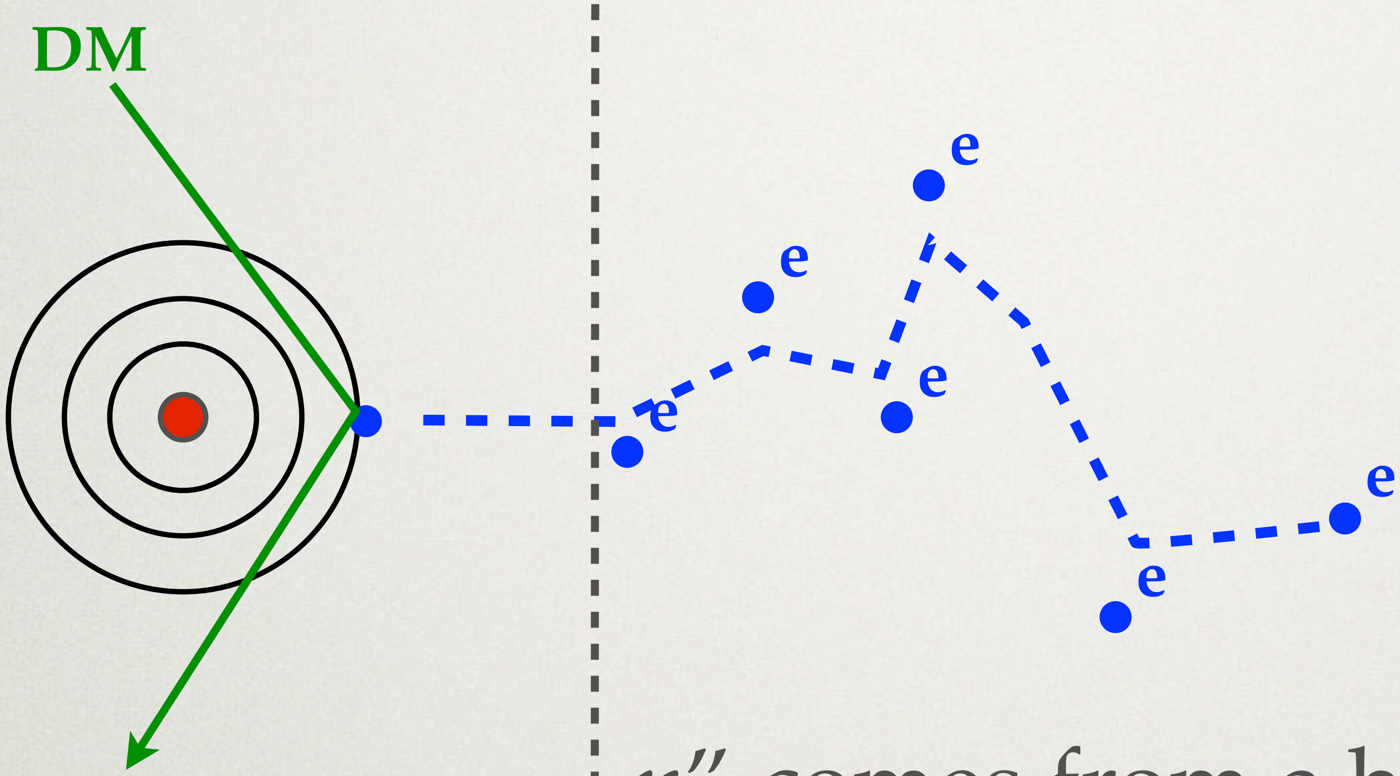
W	average energy per observable quanta
f_R	electron-ion recombination fraction
$\frac{N_{ex}}{N_i}$	ratio of excited (neutral) atoms to ions

Expected signal



$n' = 0$ or 1 with probability (1 - f_R)

Expected signal

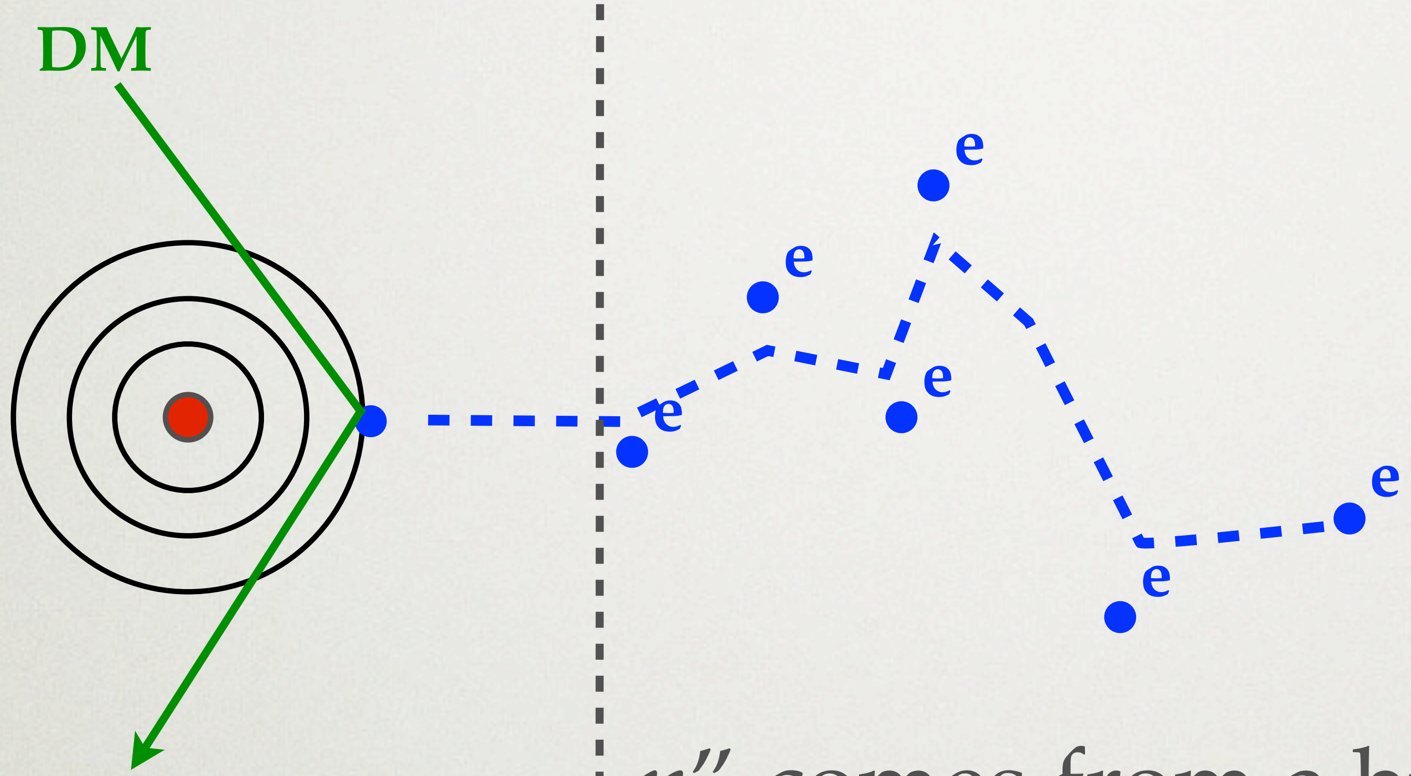


n' = 0 or 1 with probability (1 - f_R)

n'' comes from a binomial dist. with Floor(E_{er}/W) trials and $(1 - f_R)(1 - N_{ex}/N_i)^{-1}$ probability of success

The number, n_e, of detectable electrons is simply $n_e = n' + n''$

Expected signal



<u>Systematic range</u>

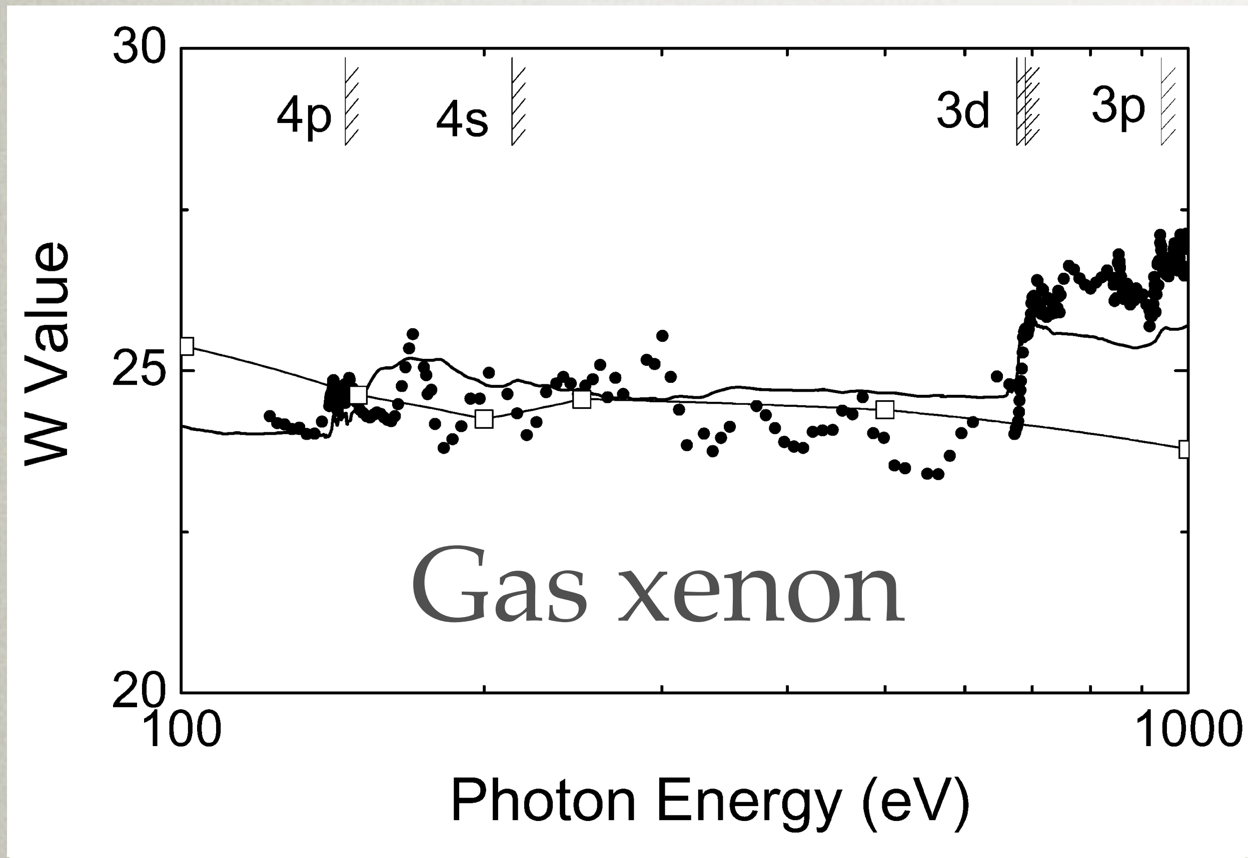
W	[12.4, 16] eV
f_R	[0, 0.2]
N_{ex}/N_i	[0.1, 0.3]

$n' = 0$ or 1 with probability (1 - f_R)

n'' comes from a binomial dist. with Floor(E_{er}/W) trials and $(1 - f_R)(1 - N_{ex}/N_i)^{-1}$ probability of success

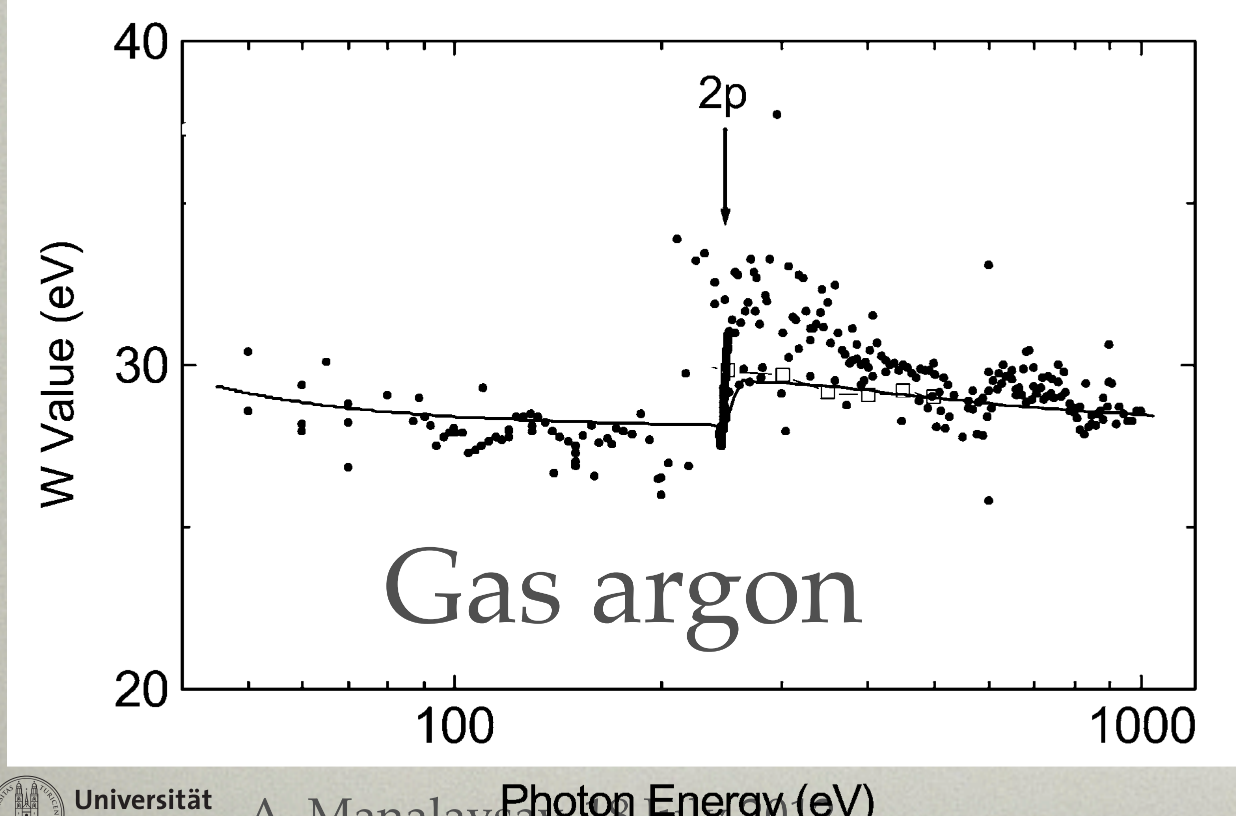
The number, n_e, of detectable electrons is simply $n_e = n' + n''$

Confidence in *W*



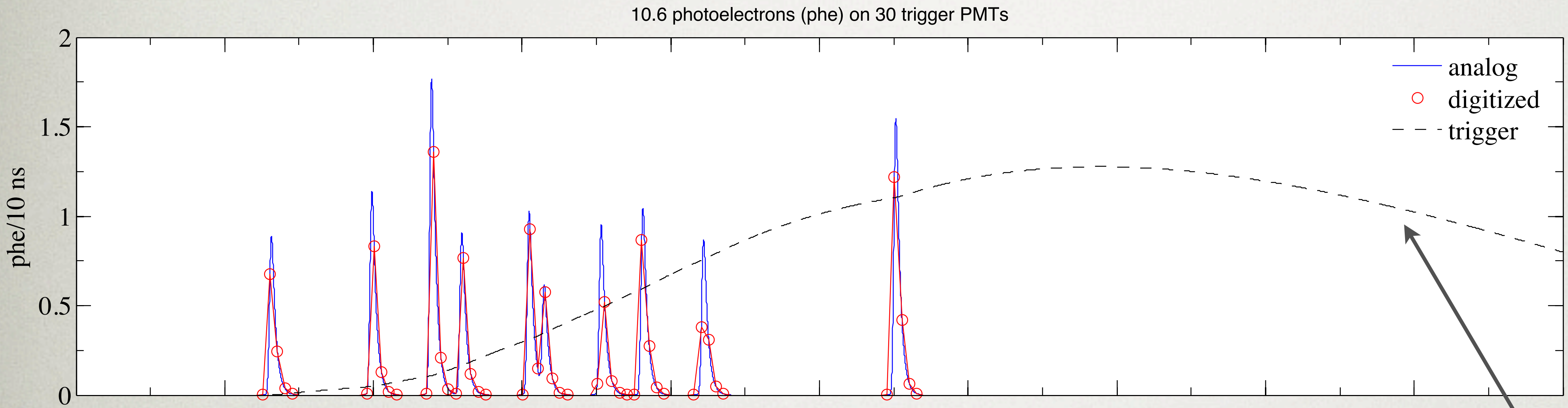
I.H.Suzuki, N.Saito, J. Elec. Spec. **119** (2001) 147

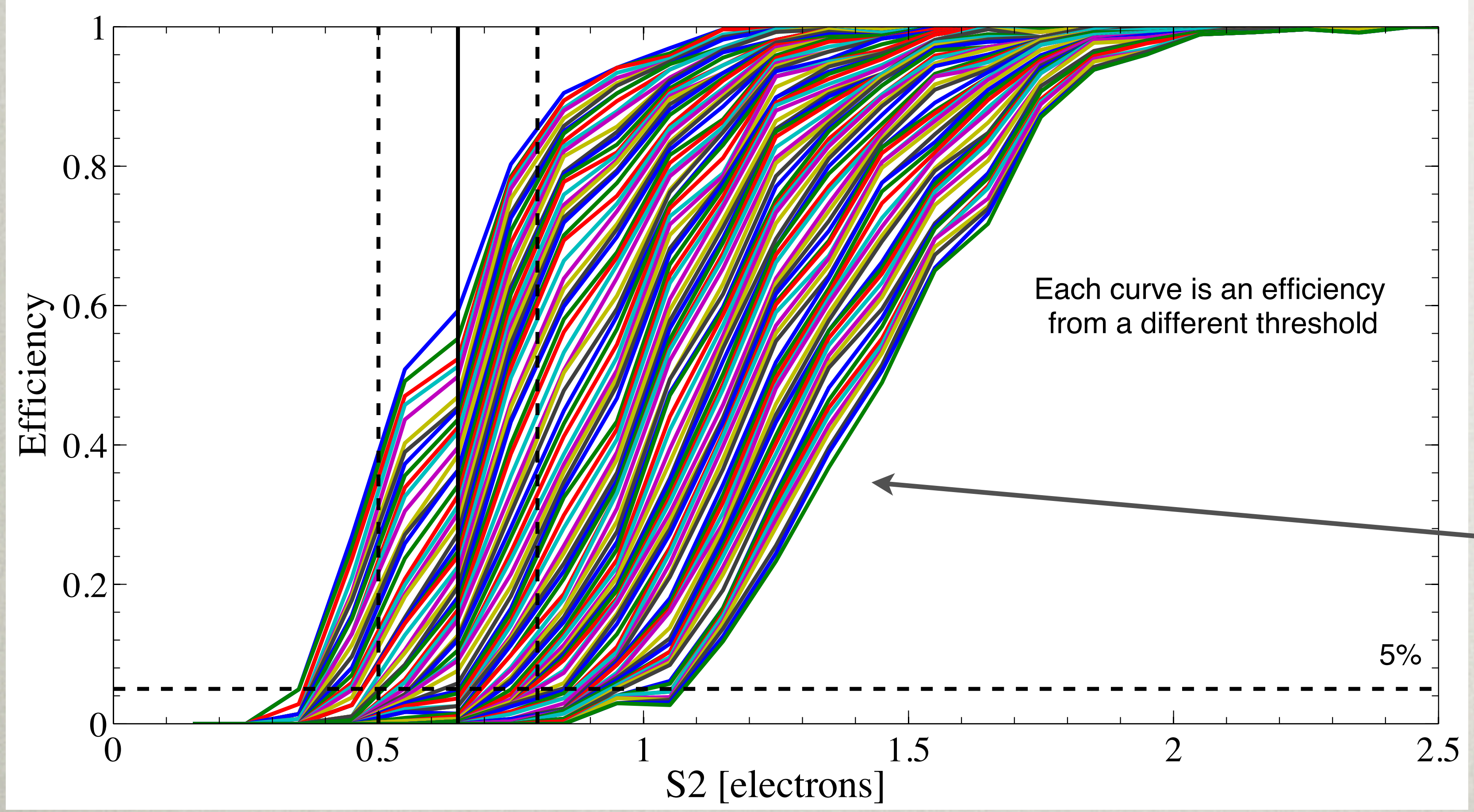
We don't have data for *W* in LXe down to ~10 eV, but these data do exist for gas xenon (almost) and gas argon. Both show no huge divergences below 1 keV.



N.Saito, I.H.Suzuki, Radiat. Phys. Chem. **60** (2001) 291

Trigger efficiency curve sim





Shaped analog signal for trigger hardware

Adjusting the trigger set point gives different detection efficiency curves. Can quantify the curve by the point there it crosses 5%, or the “turn-on”.

Trigger efficiency curve

Make a [quite safe] assumption: the efficiency turns on at, or before, the first nonzero bin in the blue histogram. This gives a range of allowed efficiency curves, whose variation is included when extracting the upper limits.